THE TECTONIC HISTORY

of the

DIAL RANGE AREA, TASMANIA.

by

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SECOND VOLUME

Submitted in fulfilment of the requirements for the degree of Doctor of Philosophy.

University of Tasmania,
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October, 1963

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF FIGURES (continued)

Chapter 6 (continued)

Chapter 7

TABLE OF FIGURES (continued)

Chapter 7 (continued)

Chapter 8

Chapter 9

Chapter 9 (continued)

Chapter 10

Chapter 12

* See back of first volume

LIST OF PLATES

Following page no.

First Volume

Chapter 1

Chapter 2

Chapter 3

Chapter 4

LIST OF PLATES (continued)

Second Volume

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Chapter 9

CHAPTER 5

STRUCTURES IN POST-MIDDLE DEVONIAN ROCKS

page no.

CHAPTER 5

Structures in post-Middle Devonian rocks

Structures in Tertiary Rocks

The Pliocene(?) Lower Coastal Surface has a seaward dip of the order of sixty feet per mile. The origin of this dip is uncertain.

The Surface could be older than the basalt, controlling the basalt slope (Davies, 1959, p.194) or the Surface could be younger than the basalt, with the slope of the Surface controlled by the thalweg of the basalt (Hills and Carey, 1949, p.37). In each case the slope is a primary feature of the Surface and is not tectonically imposed.

The slope of the Surface may, however, be a result of tilting (Davies, 1959, p.202). If so, there is an imposed tectonic warping of sixty feet per mile, towards Bass Strait. Figure 2 shows that there is no evidence of differential tilting across major faults so any tilting that occurred was uniform throughout the area.

Structures in Permian Rocks

Regional: Post-Permian epeirogenic movements are recorded in the Permian rocks of the Mersey Graben.

The graben is strongly faulted, the western margin being a complex bundle of faults, which are in a large measure pre-Permian faults re-activated in the early Tertiary. The graben is about twelve miles wide, with a structurally negative relief of about 1400 feet. Within the graben are smaller horsts and graben trending north-west. The fault strips are disrupted by rotational crossfaults trending west-north-west. The two systems are probably of early Tertiary age. There is a little-known system of faults trending north-east. One of these at Dulverton (Jennings et al, 1959) contains a dolerite dyke, so is of Jurassic age. All the north-east faults may be Jurassic. The result of the faulting episodes has been to impose numerous small faults on the Permian rocks and a regional dip northwards averaging 330 feet per mile. The largest fault has a throw of 600 feet.

The Lower Palaeozoic structures are of such an amplitude that few faults can be mapped with slips of less than 250 feet. Post-Permian faults are therefore not readily identified in the pre-Permian rocks.

The pre-Permian rocks have acquired a regional dip north of 350 feet per mile during the Jurassic and early Tertiary faulting. They do not contain any major faults of this age, as far as is known, but may contain minor structures of Tertiary age. An examination was made of Tertiary minor structures in the Permian rocks at the Illamatha Colliery in order to determine their type and orientation.

<u>Illamatha Colliery</u>: The Illamatha Colliery lies in Permian rocks near the western edge of the major Mersey Graben. The Colliery lies on a small structural terrace bounded by north-west faults which downthrow east. A narrow horst trending north-west, seventy feet west of the main shaft, is bounded by normal faults. Between the horst and the western limit of the workings is a region of rotational faults.

The succession in the workings is:

Sandstones................. about	30 feet thick
Mudstone ("clod")...............	3 feet
Coal..........................	2 feet
Clay..........................	6 inches
Sandstone.....................	4 feet plus.

The total cover at the time of faulting was between one and two thousand feet.

The normal, or graben-forming faults, have smooth polished surfaces. There is a well-marked lineation parallel to slip which will be denoted '<u>a</u>'. A faint striation perpendicular to the slip at the intersection of complementary joints with the fault is denoted '<u>b</u>'. Some fault surfaces have the two sets of lineations almost equally well developed.

Figure 15 shows faults of more than two feet throw. The average hades are 16 degrees to the southwest, with standard deviation of 9 degrees, and 25 degrees to the northeast, with deviation of 8 degrees. Smaller faults

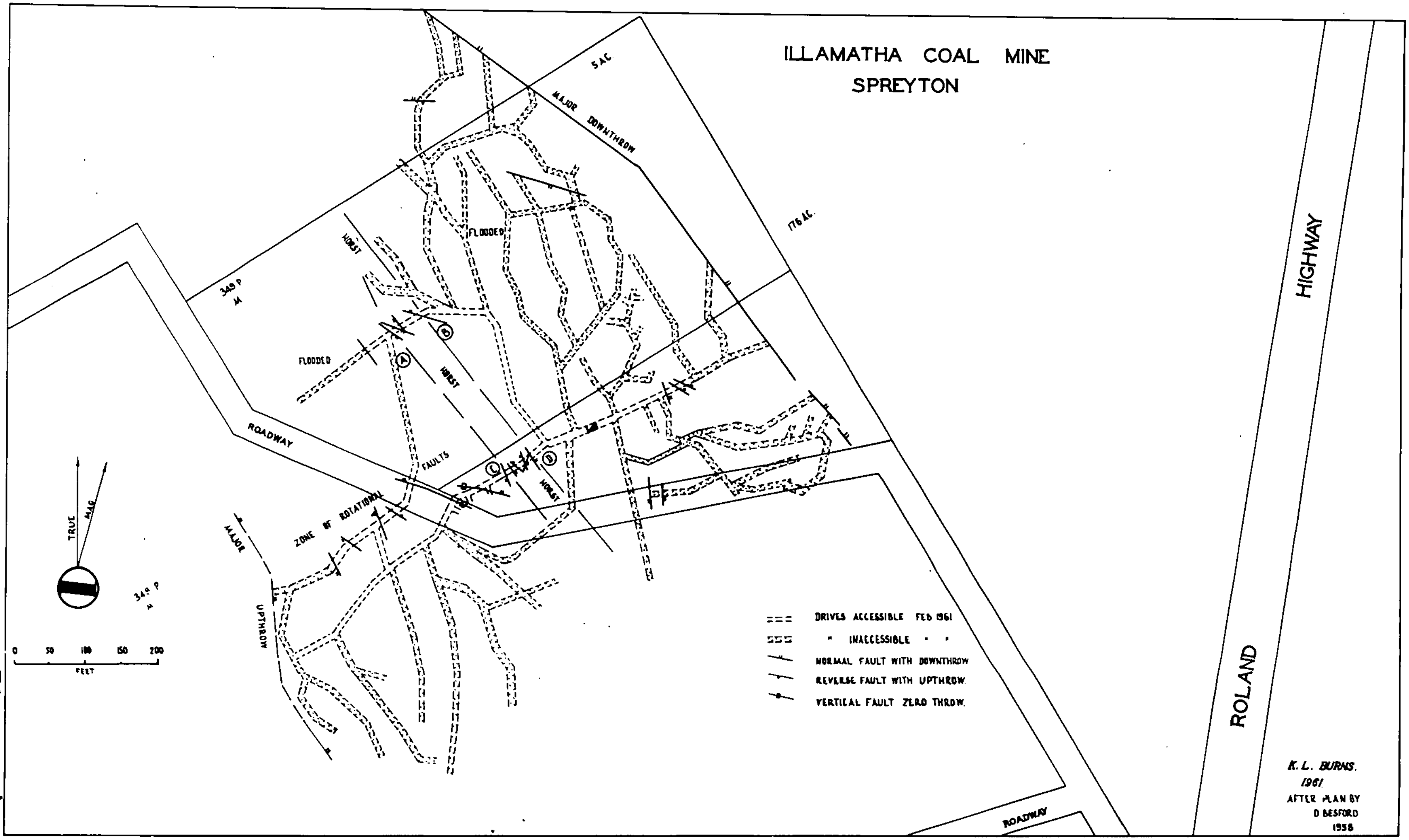

ILLAMATHA COAL MINE
SPREYTON
MAJOR DOWNTHROW
SAC
176 AC.
349 P
M
HORST
FLOODED
FLOODED
HORST
FAULTS
HORST
ZONE OF ROTATIONAL
MAJOR
UPTHROW
ROADWAY
ROADWAY
ROLAND
HIGHWAY
TRUE
MAG
349 P
M
0
50
100
150
200
FEET
DRIVES ACCESSIBLE FEB 1961
" INACCESSIBLE " "
NORMAL FAULT WITH DOWNTHROW
REVERSE FAULT WITH UPTHROW
VERTICAL FAULT ZERO THROW
K. L. BURNS.
1961
AFTER PLAN BY
D BESFORD
1958

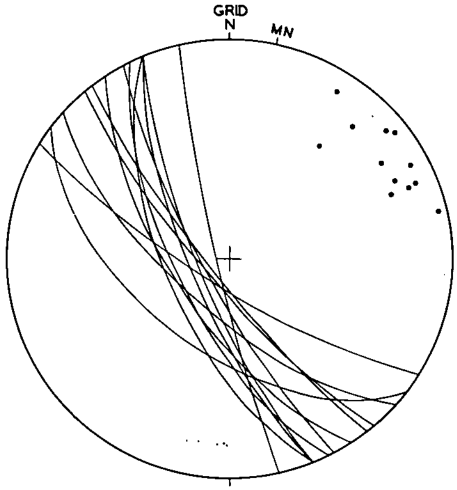
Figure 14

and joints have the same attitudes. The phenomenon of differing hades for the two sets of faults is real despite a low sampling frequency, as the acute bisectrix of individual joint rhombs has an appreciable deviation of plunge towards the north-east from vertical.

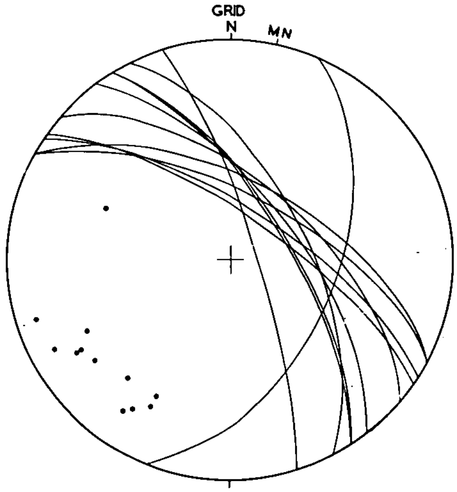
Figure 15c shows the fault intersections. The maximum is overlarge, emphasising a close parallelism of several faults which can only be accidental at this sampling frequency, and is properly evaluated in terms of the lower contours. However, it illustrates a condition observed in the field - the '<u>b</u>' lineation never pitches horizontally in the fault surface, but has an appreciable angle of pitch. The axes of folds are similarly oriented. The '<u>a</u>' lineation or slip, does not pitch at ninety degrees but has been observed with pitches as low as seventy degrees to the south.

The normal faults are not, therefore, oriented symmetrically with respect to the geographic ordinates. Their intersections plunge, usually north, and the acute bisectrix of the dihedral angle between the fault systems hades to the north-east.

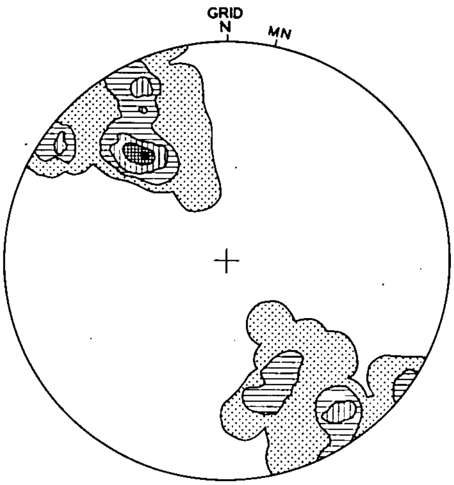
The minor horst of figure 14 is of variable profile. The most likely reason is that individual faults have variable strike along their length. This is also indicated by figures 15a and 15b where faults of the same kind



(a) NORMAL FAULTS DOWNTHROWING SOUTHWEST.

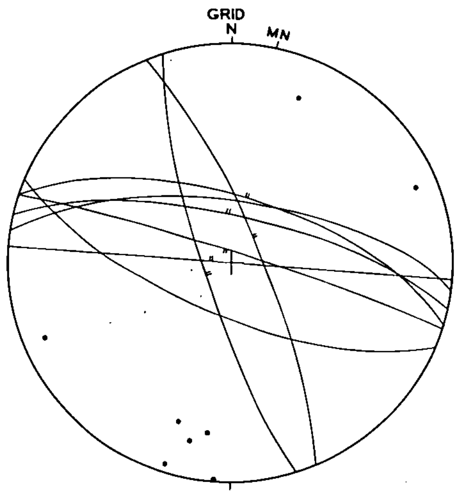


(b) NORMAL FAULTS DOWNTHROWING NORTHEAST



(c) INTERSECTIONS OF NORMAL FAULTS OF OPPOSITE THROW

CONTOURS 0-5-10-15 %
MAXIMUM 19·2 % . 121 INTERSECTIONS



(d) ROTATIONAL FAULTS

TICKS ON DOWNTHROWN SIDE

TERTIARY FAULTS - ILLAMATHA COLLIERY

Figure 15

tend to intersect near the direction of slip.

Closely associated with the normal faults are folds of two kinds:

> "Slip folds" (plate 12) are named in the sense of Becker (1882, pp.156 et seq.) and are formed by displacement on close-spaced minor faults. These are confined to the competent sandstones.
>
> "Ductile shear" folds (plate 13) formed by extrusion flow (cf. Jaeger, 1962, pp.147-8) are confined to the less competent coal and clod. These occur where the hanging wall has moved away from the footwall, sometimes as much as eighteen inches, and where the clod has been forced into the gap. Some faults still contain open cavities up to six inches wide, so the flowage does not always completely close the gap.

In the "ductile shear" folds, the laminae describe smooth curves, but the accommodation was almost entirely along conjugate ductile shears hading at about fifty degrees on the fold limbs. The shears curve over the fold crests. The pattern resembles that of concentric shear joints (cf. de Sitter, 1956, figure 124) but it not equivalent, the coal being laterally extruded toward the low pressure area at the faults.

The rotational faults have a mean azimuth near 290. The fault planes carry an '<u>a</u>' lineation pitching 65 degrees north, and a '<u>b</u>' lineation with observed pitches ranging from five to eleven degrees north. The fault surfaces are steep and often are curved. One fault splays, the main fault hading near twenty-five degrees north-west, and three splays hading 0, 18 and 25 degrees north-west. Another

Plate 12

"Slip fold" in sandstone, Illamatha Colliery.

Hammer handle one foot long.

fault changes hade from ten degrees south-west to eleven degrees north-east, in the height of a drive. The faults have rotational movement; in one the stratigraphic throw changes from one inch down to three inches up in a distance of twelve feet. Portions of many of the faults have reverse movement.

The normal faults have a mean azimuth of 320, the rotational faults, of 290. The two sets correspond to the 333 and 287 maxima of Banks (1958, p.245).

The faults are usually oblique slip. However, the pitch of the slip in the fault plane varies between individual faults and probably along a single fault, so the regional rotation of the stress field as proposed by Williams (1958) or Bott (1959, p.110) is inapplicable. The faults probably undulate co-axial with the slip which means that in general the angle in the fault plane between the directions of slip and hade is greater than zero.

The occurrence of ductile-shear folds in the coal indicates a net tension normal to, with pulling apart of, the fault planes. Using this fact and the methods of Anderson (1951, pp.11, 155), the stress field can be calculated (Appendix 1).

This work shows that well developed minor structures were generated during the Tertiary, which need to be considered in work on lower Palaeozoic structures.

Plate 13

"Ductile-shear" fold in coal and clod, Illamatha Colliery.

Width of field eight feet.

Structures in the Eucenana Beds

The base of the graded sandstone of plate 11 has a bottom structure superficially resembling the interference ripple marks of Shrock (1948, fig.77) or the periclinal ripple marks of Ten Haaf (1959, fig.10B). The rounded crests average 0.5 inches diameter, with flat-bottomed or angular troughs. However, each crest corresponds with a large fragment of claystone in the base of the bed, the underlying mudstone having been forced upward into the sandstone as incipient flame structures in between the claystone fragments. In the terminology of Kuenen (1957), the structure is a type of load-casting.

In the mudstone beds of unit 3, there are some coarse laminae from 0.1 to 0.2 inches thick, which are penetrated at the base by flame structures from the underlying bed. The flames overturn in either of two opposite directions, and are injected at the nodes of sedimentary boudins.

The top of one mudstone bed is folded over sedimentary boudinage in its interior, to give a structure superficially resembling ripple marks, but, with a wave-length of 1.2 inches and amplitude of 0.05 inches, having the improbable ripple index of 24. The ridges are asymmetrical, forming discontinuous, overlapping ridges in plan, which are between two and three inches long. However, the laminae show no thickening across the crests.

The very thick sandstones of unit 3 contain interstratal contortions, confined to the interiors of the beds, and not extending to the upper or lower surfaces.

In the upper part of No.3 lens, Halletts Quarry, where the sandstones are only a few inches thick, they show small folds of six inches wavelength and two inches amplitude which are asymmetrical with broken eastern limbs.

Several tight folds occur in mudstones between limestone boulders at the base of No.3 lens, Halletts Quarry. One anticline, shown in plate 14, is isoclinal, with an amplitude of three inches and wavelength of 1.5 inches, the cylindrically bent axial surface curving to follow the outlines of the boulders. The word "bent" is used, rather than "folded", as folded implies a superimposed bending, and it is likely the fold was generated on a curving axial surface. The bedding within the fold is thickened at the crest to double that at the limbs, but the most delicate sedimentary structures, including laminations and a small scour-and-fill structure, are preserved. There is no trace of cleavage or other tectonic structures within the fold. The fold is considered due to compaction, the mudstone having been squeezed upward between the limestone blocks while still soft.

A number of open anticlines and synclines occur, draped over or under limestone blocks, such as in plate 15.

Plate 14

Isoclinal fold in mudstone, Eugenana Beds, Halletts Quarry.

Natural size.


1829

Although the laminations form arcs in these folds, ductile shear planes are strongly developed in each limb, curving over the crest. The shear planes are highly polished and one contains a thin, slickensided sheet of calcite. These shear planes occur in the terra rossa of unit 2 and mudstone of unit 3, and, in places, form two intersecting sets which follow the outlines of the boulders. These structures may be tectonic and indeed have some resemblances to the ductile shear folds of the Illamatha Colliery which formed as a result of the Tertiary epierogeny. They could also be due to loading in the Permian, the mudstone being squeezed differentially with respect to the limestone boulders. They were probably formed in indurated beds during the Tertiary epierogeny.

No.3 lens, Halletts Quarry, is gently folded (figure 13b). In the higher portion of the lens, several joints cross the beds forming a conjugate set with near-vertical line of intersection. Affecting several beds at a time, the joints are tectonic.

In general, the post-depositional structures described, fall into two classes. There is boudinage, and folding over boudins; periclinal folding over large mudstone pellets and tight isoclinal folding of beds squeezed in between boulders. These structures were formed in deformation or unconsolidated rock.

Plate 15

"Ductile-shear" compaction fold at base of cave fill,

Halletts Quarry.

Hammer head six inches long.

Ductile shear folding and jointing of the beds occurred when the rock was indurated, conceivably during Permian loading or the Tertiary epierogeny.

All the post-depositional structures can be satisfactorily assigned to known events, the deposition of the Permian and the post-Permian epierogenies, without postulating additional tectonic movements. The scale of the structures and their limited occurrence makes it highly unlikely that any post-Devonian major orogeny did occur.

CHAPTER 6

STRUCTURES IN ORDOVICIAN ROCKS

CHAPTER 6

Structures in Ordovician Rocks

Eugenana

Introduction: The Melrose Basin (figure 16) is a brachysyncline, elongated north-south. Gordon Limestone in the centre is surrounded by a rim of Moina Sandstone. The rocks underlying the Moina Sandstone are Precambrian at the north end of the Basin and Cambrian in the south, so the Basin overlies the margin of the Dundas Trough. The Basin rim is not continuous but is interrupted by Devonian and Tertiary faults.

At the Eugenana quarries (see figure 12) at the northern end of the Melrose Basin, three generations of folding are recognised and are dated as pre-Upper Devonian.

First Generation Folding: The Gordon Limestone carries a well marked S-surface, foliation. The affine deformation of primary structures shows the foliation is penetrative. At the present time it has a discrete appearance, out-cropping as parallel planes of about one-eighth of an inch separation, due to non-affine reworking in the second period of movement. The foliation is coated, in places, with films of slickensided calcite and graphite. The orientation is fairly uniform throughout the basin, at 65E007 (figure 17a).

Bedding has been obliterated in the limestone, so that

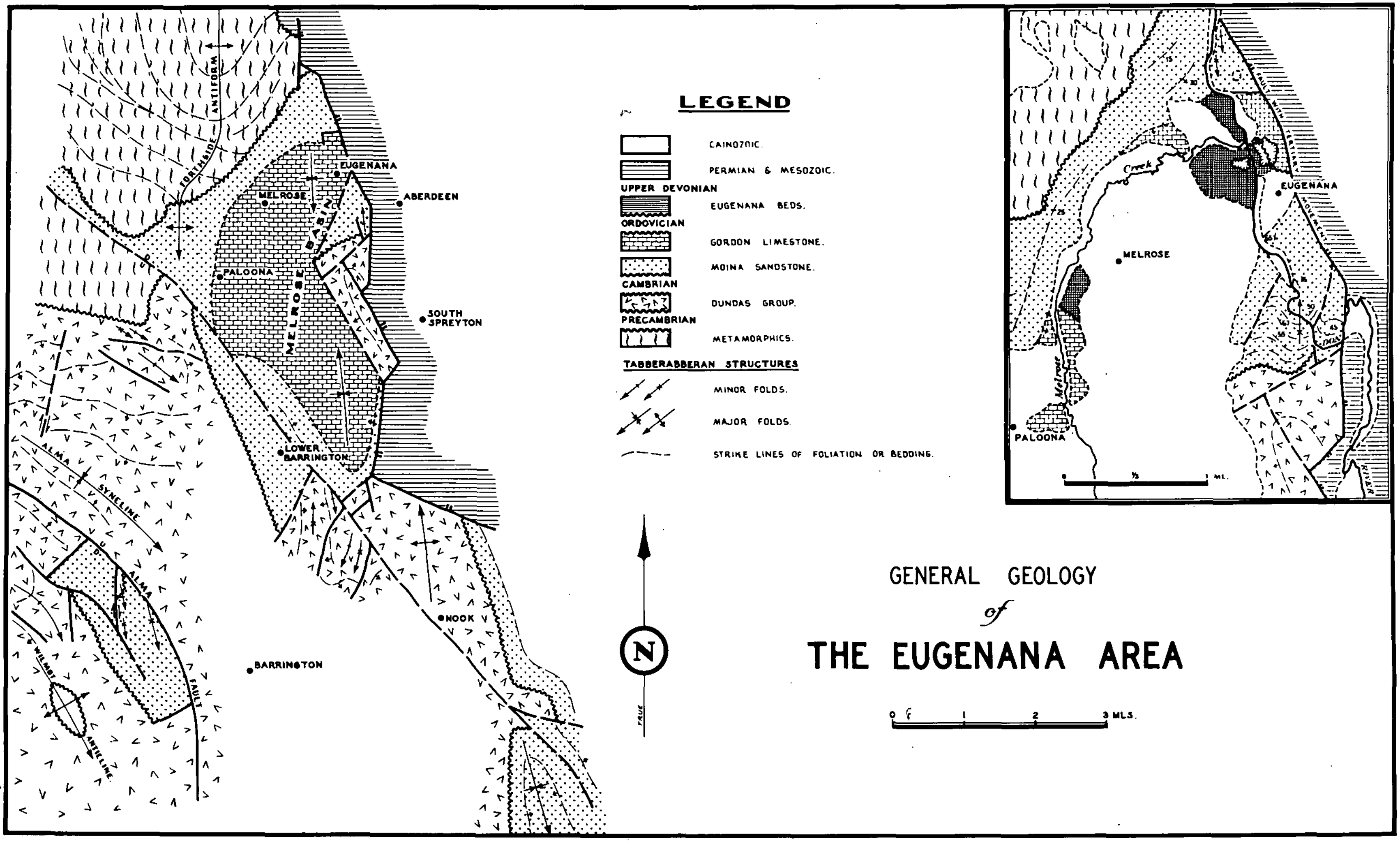

GENERAL GEOLOGY of THE EUGENANA AREA
LEGEND
CAINOZOIC.
PERMIAN & MESOZOIC.
UPPER DEVONIAN
EUGENANA BEDS.
ORDOVICIAN
GORDON LIMESTONE.
MOINA SANDSTONE.
CAMBRIAN
DUNDAS GROUP.
PRECAMBRIAN
METAMORPHICS.
TABBERABBERAN STRUCTURES
MINOR FOLDS.
MAJOR FOLDS.
STRIKE LINES OF FOLIATION OR BEDDING.
0 1 2 3 MLS.
0 ½ 1 ML.
N
TRUE
FORTHSIDE ANTIFORM
MELROSE BASIN
ALMA SYNCLINE
ALMA
WILMOT ANTICLINE
FAULT
EUGENANA
ABERDEEN
MELROSE
PALOONA
SOUTH SPREYTON
LOWER BARRINGTON
NOOK
BARRINGTON
Creek
Melrose

Figure 16

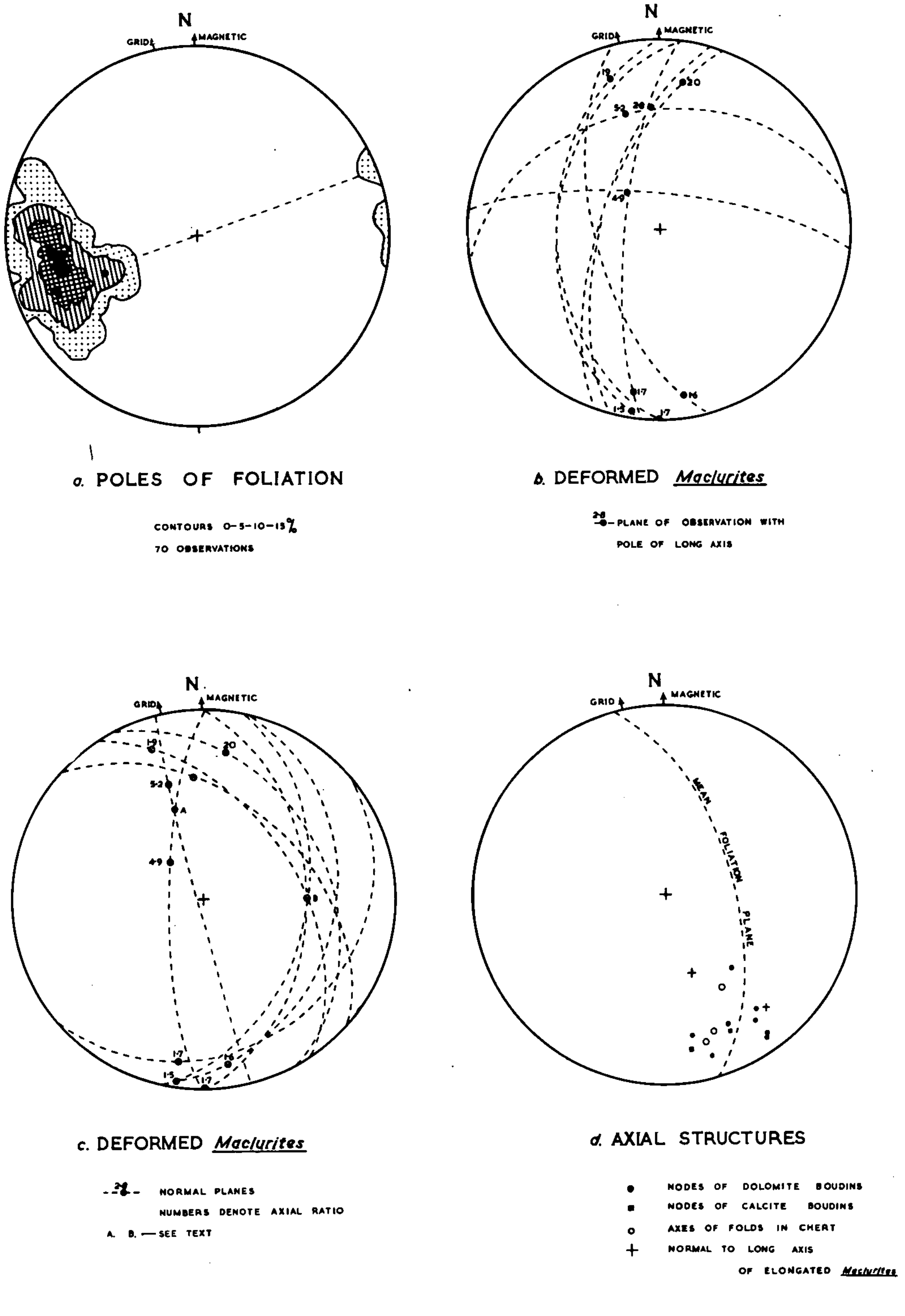
the only folds observed are in thin lenses of chert in the B.H.P. Quarry (figure 12). The folds are open, of one-half to two inches amplitude and have axes pitching close to fifteen degrees south in the foliation. One lens is folded into a minor anticlinorium (in the sense of van Hise, 1896). The foliation in the limestone is continuous with the axial surfaces of the folds in the chert, the two structures together describing smooth continuous curves (figure 18). The folds and foliation are therefore the same age, and the foliation is a structure generated parallel to the axial surfaces of the folds.

Within the limestone are lenses and diffuse patches of dolomite. Seams of dolomite and calcite are found lying parallel to the foliation and drawn into boudins. The axes of the boudins plunge twenty degrees south in the foliation plane and were formed by deformation with the foliation as the plane of gliding, in the sense of Anderson (1948, p.106).

The index fossil, Maclurites, occurs in the limestone. Some thirty fossils were found in the B.H.P. Quarry, and in eight of these the complete basal surface is exposed. The basal surface is recognised by the presence of the nucleoconch, and four whorls, the outermost whorl expanding rapidly. The shape of the fossil is such that, for these basal structures to be visible, the outcrop surface must lie within a few degrees of the basal plane of the fossil (Banks, M.R., pers. comm. also Banks and Johnson, 1957).

The axes of the elliptical basal section have been measured (a/2 and b of figure 19), and the axial ratio calculated as a/b. The observed ratios fall into two groups, one with ratios from 1.5 to 2.0 and the other with ratios near 5.0. The usual ratio for the undeformed fossil is calculated from the observations of Banks and Johnson (1957) to be 1.5 to 1.7, so that ratios near 5.0 imply deformation of the fossils.

The number of observations has been severely limited by several restrictions. First, a single element of the fossil, the basal plane, is being observed, and it is a matter of chance that this will be exposed on the outcrop surface. Slightly less weathering, and the nucleoconch will be buried, slightly more and it will have been removed. Second, the direction of extension pitches steeply in the foliation so that the only fossils showing tectonic elongation are those with their basal planes nearly perpendicular to the foliation, and with their original long axes somewhere near the direction of tectonic elongation. If the long axis is originally somewhere near horizontal, the deformation will reduce the elongation. Thus the two highly deformed fossils are rare phenomena, and their discovery is highly significant. It may be



FIRST GENERATION FOLDING EUGENANA

Figure 17

noted that M.R. Banks (pers. comm.) in collecting data for the paper with Johnson, discarded all measurements from Eugenana because of their "abnormality".

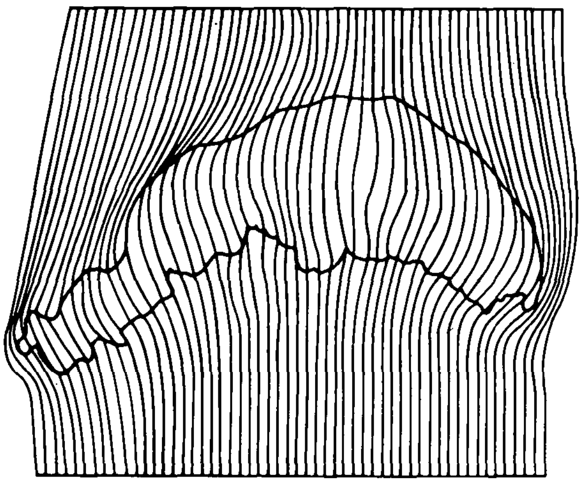
Figure 17b shows the orientation of the long axes of the fossils. The intersection of the normal planes, the usual test for linear fabric (Clark and McIntyre, 1951b), is at A for the highly deformed fossils, and near B for the less deformed, in figure 17c.

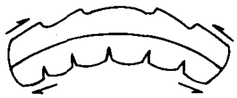
B is probably lying in bedding, an orientation to be expected since the fossils usually have their basal planes parallel to bedding. In this orientation the direction of tectonic elongation is normal to the basal planes so no change in shape of the basal planes will occur. A line in the foliation at ninety degrees to A should be 'c' in Anderson's terminology and is plotted in figure 17d as the 'normal to the long axis'.

In figure 17d the axes of folded chert lenses, nodes of boudins, and normals to the long axes of highly deformed *Maclurites*, plot in a small area of the Lambert net. This area is intersected by the trace of the mean foliation. The orientations of these several structures and their styles as described above are consistent with their having been formed in one single episode of deformation.

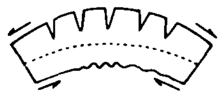
The bulk strain of the rocks involved in the first generation of folding at Eugenana may be computed from the

LENS OF LAMINATED CHERT IN FOLIATED LIMESTONE





INCONGRUENT FOLDING



COMPETENT FOLDING

SECONDARY STRAINS

FLOW NET CORRESPONDING TO PREVIOUS FIGURE

FOR EXPLANATION SEE TEXT

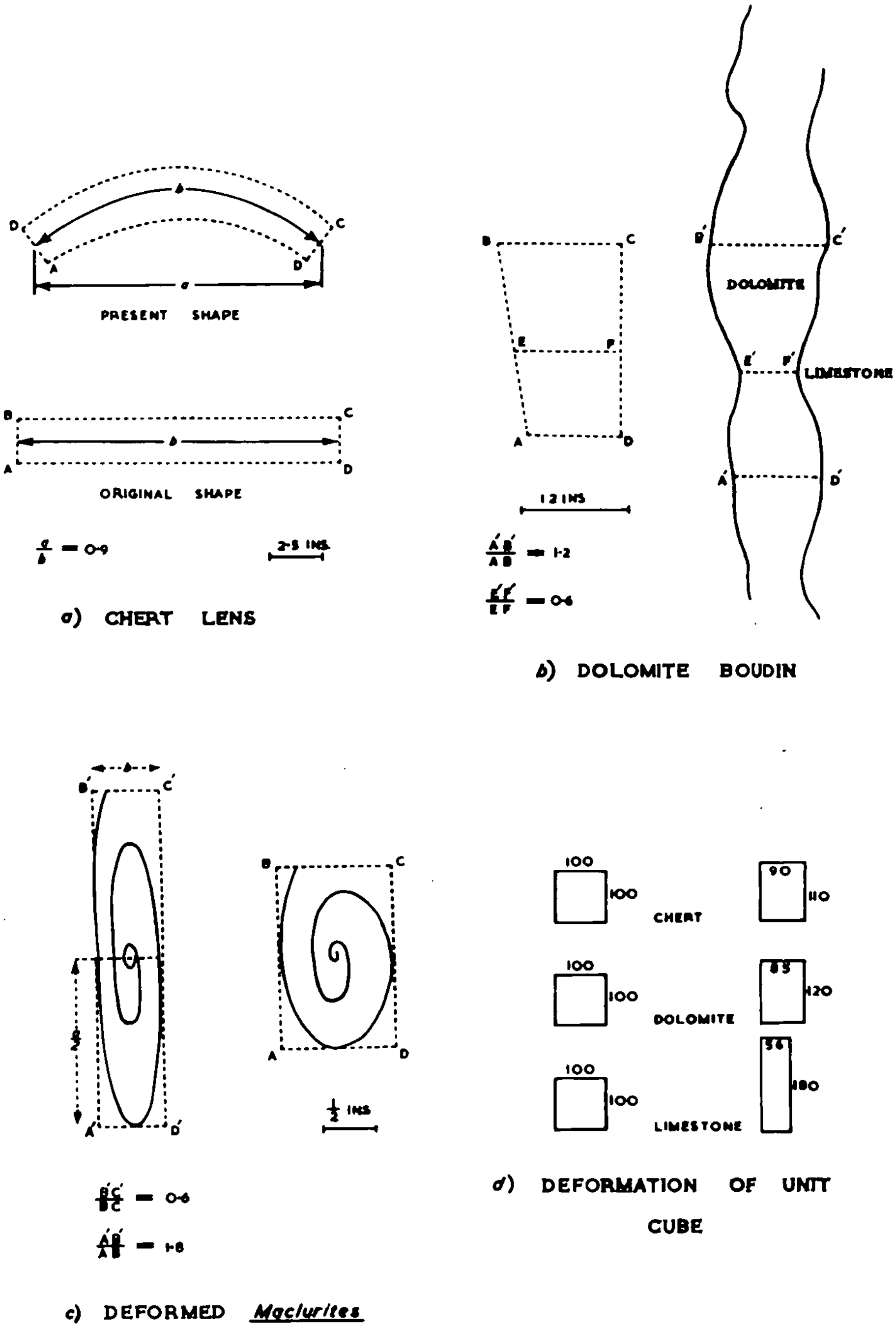
INCONGRUENT FOLDING IN LIMESTONE
EUGENANA

Figure 18

folded chert lens, dolomite boudins and elongated *Maclurites*.

A folded chert lens was photographed, and the traces of foliation and axial surfaces of the folds, determined in the field, as in figure 18. Using modified Buskian methods (modified to allow for divergence of the traces, as in Carey, 1954, p.95), the "flow net" of the same figure was constructed. The foliation planes in the limestone form smooth curves, confirmed in the field, which are continuous with the axial surfaces of the chert folds. In the reconstructed flow net, the "flow lines" (Carey) or "pq planes" (Anderson, 1948, p.106) diverge at the base of the chert, the separation of the flow lines increasing by 120 percent. It is shown in Appendix 2, that assuming Newtonian viscosity as the only important strain parameter, the ratio of viscosities for chert:limestone is 144:100. Holmquist (1929) has named folding of this type "incongruent", and considers that the "ejectif" wedges of limestone at the base of the chert are due to different wavelengths of flexural folding. However, the flow net shows the flexural component of movement is insignificant. The breaks in the base of the chert are openings, resembling sedimentary flame structures, which are due to tension. The tension in the present case results from the divergent flow at the base of the lens. Complementary to the divergent flow at the base there is convergent flow at the top of the lens. The strain pattern of the fold is thus the reverse of the flexural situation. The chert is folded into a broad arc, defined by the "enveloping surface" and the ratio of chord:arc length is about 31:27. This may indicate a lateral shortening to the order of 90 percent. (By a shortening to 90 percent, it is meant that a line of original length of 100 units, is reduced in length to 90 units). If deformation occurred in "pure" or "irrotational" shear, this implies a vertical extension of 110 percent, using methods of Chamberlin (1910), which were discussed by Bucher (1933, pp.151-6) and de Sitter (1956, p.189).

The thickness of the nodes of the boudins in dolomite is near half the thickness at the anti-nodes. Assuming that there has been no alteration in thickness at the anti-nodes, the extension can be calculated. The calculation assumes that the area of dolomite between the anti-nodes is conserved in profiles normal to foliation and the boudin axes. From the boudin of figure 19b, an extension to 120 percent is estimated. Assuming that boudins are formed in irrotational strain as is likely from Ramberg (1955), Rast (1956) and Coe (1959), there is a lateral shortening to 83 percent. The shortening is concentrated at the nodes, reaching a localised extreme value of 60 percent.



STRAIN IN THREE LITHOGIES EUGENANA

IN EACH CASE ABCD IS TRANSFORMED TO A′B′C′D′ AT CONSTANT VOLUME

FOR EXPLANATION SEE TEXT

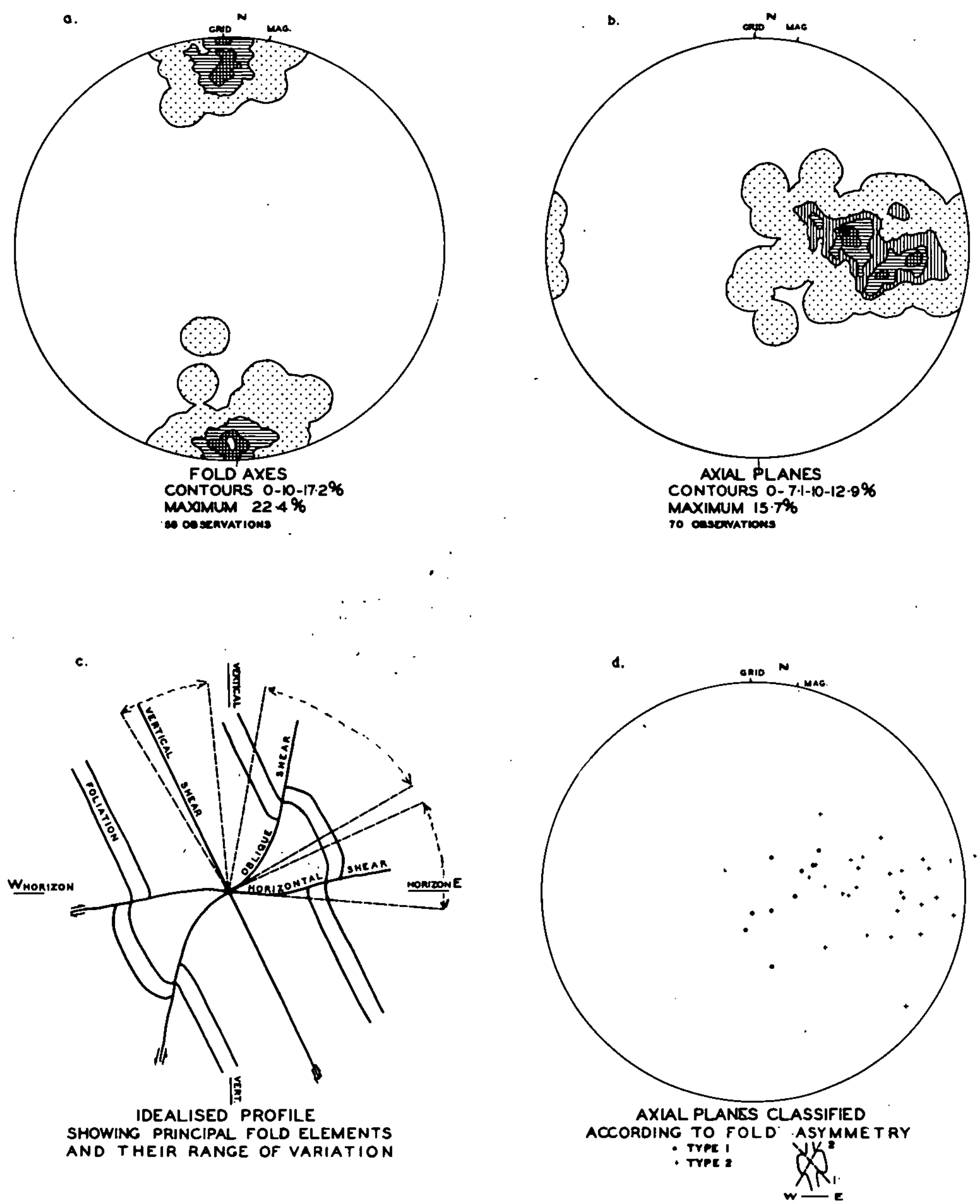
Figure 19

The highly elongated _Maclurites_ fossils have an axial ratio of 52:10. The original axial ratio was near 16:10 from Banks and Johnson (1957). Irrotational deformation implies a vertical extension to 180 percent, and a lateral shortening to 60 percent.

Assuming irrotational strain, there was a vertical elongation to 180 percent in limestone, 120 percent in dolomite and 110 percent in chert. There was a lateral shortening to 56 percent in limestone, 85 percent in dolomite and 90 percent in chert. These figures are reasonable for these lithologies.

Second Generation Folding: The limestone contains a set of rounded open folds ranging from several inches to five feet in wavelength and from a fraction of an inch to two feet amplitude. The folded S-surface is the foliation formed in the first deformation. There was some difficulty in excavating this cleanly to obtain direct measurements of fold axes, so in some cases the axis was determined by computation of the intersection of the foliation with the trace of the axial surface. This method is only applicable to small folds, which are virtually "perturbations" of a uniformly oriented foliation. The fold axes have a mean azimuth of 170, with plunges up to 20 degrees towards both north and south (figure 20a).

The azimuth of the axes is close to that of the first



SECOND GENERATION FOLDING—EUGENANA

Figure 20

generation folds but the style is very different. The axial planes crosscut the foliation instead of lying parallel to it, and the folds are a refolding of the foliation. The dispersion of foliation poles of figure 17a is due to this refolding.

Fine striations on the foliation occur in one fold at Rundles Quarry and the lines which lie in the foliation perpendicular to the striations, have the same orientation as the axes of the second folds.

Critical evidence that this is a later phase of deformation than the first generation, is afforded by examples of refolding of boudinage (first generation) in several folds, and the offsetting of boudinaged calcite seams on "oblique shears" of the second generation folds.

The first deformation was by affine slip on infinitesimally spaced foliation surfaces, as shown by the continuity of deformed fossils. However, the foliation now outcrops as a regular fissility on one-eighth to one-quarter of an inch spacing. This spacing is due to reworking, by non-affine slip, of the foliation, as shown by the stepped calcite seam of plate 16. The seam has been offset on discrete microlithons.

The folds are usually small-scale undulations. There are rounded undulations, carinate undulations and zig-zag undulations.

Plate 16

Calcite mylonite on an oblique shear refolded by slip on discrete foliation surfaces. B.H.P. Quarry, Eugenana, looking south.

Scale: 4.4 centimetres long.

The axial surfaces of the rounded undulations usually dip steeply west (figure 21*a*) but there are several examples with axial planes dipping gently west, forming part of folds of conjugate profile (figure 21*m*).

The carinate undulations have an axial-surface fault which dies out into rounded undulations at its ends to form the "complete fault" of Nevin (1942, figure 70), as in figure 21, *b* and *c*.

In the zig-zag undulations, the foliation is sharply "kinked" across a pair of parallel shear planes (figure 21e).

In places the axial surfaces of the carinate folds continue upwards into large, rounded folds facing east (figure 21, *g*-*k*). The fold profile and kinematics of these larger folds approximate the "oblique-shear" folds of de Sitter (1956, figure 128), and Hills (1953, figure 49c). Oblique-shear folds are abundant in a small part of the south face of the B.H.P. Quarry.

Occasional west-facing folds occur, which with juxtaposed east-facing folds form composite folds of conjugate profile (Johnson, 1956). A complete conjugate fold consists of two intersecting sets of monoclinal folds (in the sense of Kelley, 1950), of opposed facings, but at Eugenana the east-facing set is predominant.

The fold style can be regarded as generally of

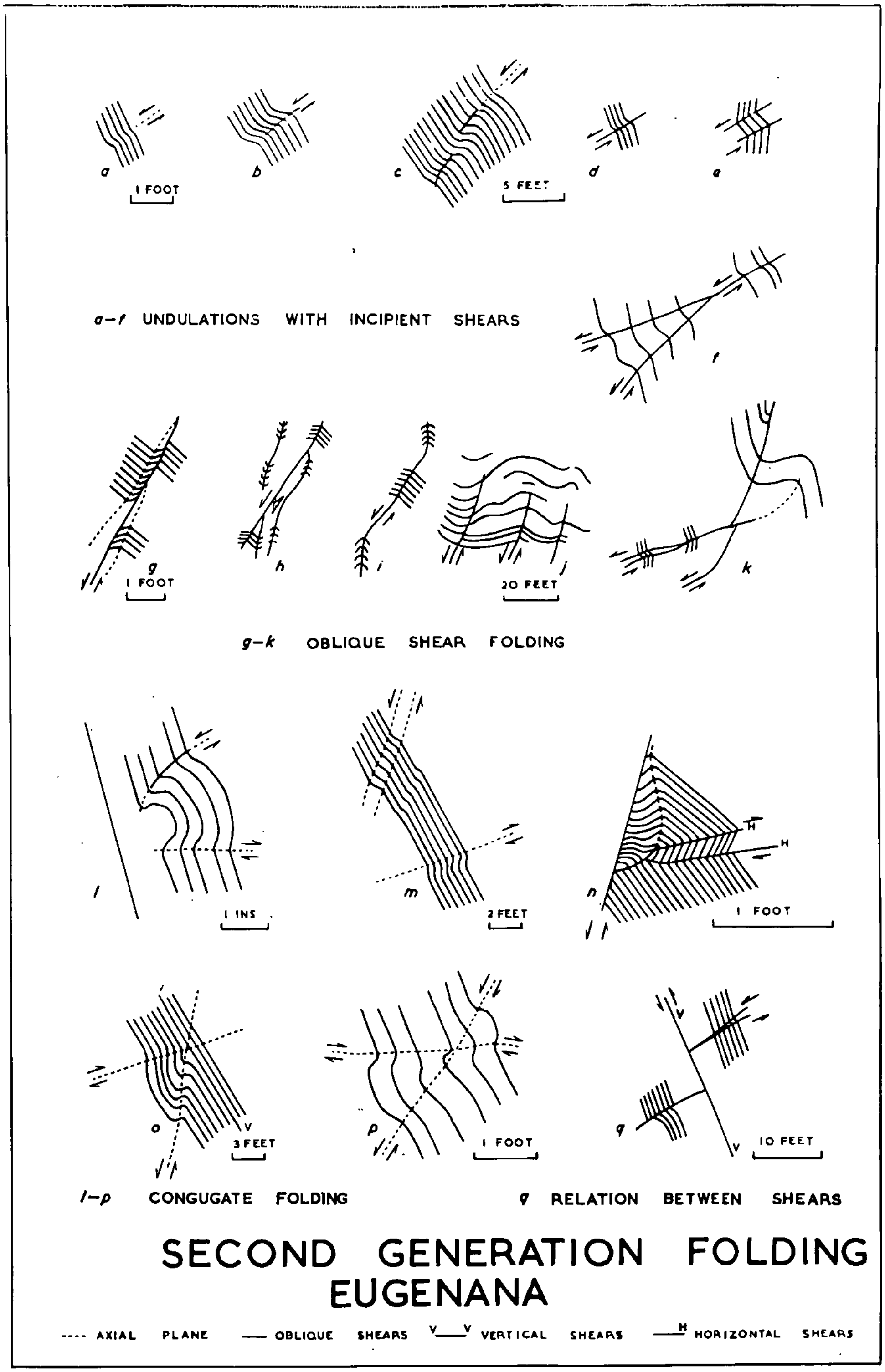

a
b
c
d
e
1 FOOT
5 FEET
a–f UNDULATIONS WITH INCIPIENT SHEARS
f
g
h
i
j
k
1 FOOT
20 FEET
g–k OBLIQUE SHEAR FOLDING
l
m
n
1 INS
2 FEET
1 FOOT
H
o
p
q
3 FEET
1 FOOT
10 FEET
l–p CONGUGATE FOLDING
q RELATION BETWEEN SHEARS
SECOND GENERATION FOLDING
EUGENANA
---- AXIAL PLANE
—— OBLIQUE SHEARS
V——V VERTICAL SHEARS
——H HORIZONTAL SHEARS

Figure 21

oblique-shear type, with occasional conjugate folds formed where the conjugate shears are well developed.

In the south face of the B.H.P. Quarry are several strong shear surfaces, which have a layer up to one inch thick of strongly lineated calcite. The shears form two distinct sets - "vertical shears", subparallel to foliation, and "oblique shears" which dip steeply west. A third type, "horizontal shears", dips gently west, and occurs only in the interior of well-developed conjugate folds. The three types are illustrated in figure 21, and in figure 22a, b.

The oblique shears dip about forty-five degrees west and are frequently "knick surfaces" to zig-zag or carinate undulations which have movement in the normal sense (that is, hanging-wall downthrown). They pass upwards into oblique shear folds and in addition, crosscut the axial surfaces of other oblique shear folds (figure 21k). This means that the oblique shears were formed during folding, but later than some of the folds. It may be noted that the oblique shears and axial planes of folds are spread over much the same field (figures 22a and 20b) and that the shears curve about axes parallel to the folds (figure 21k).

The vertical shears are possibly younger than the oblique shears as in one place a strong oblique shear is

Plate 17

Second-generation conjugate fold of foliation.

B.H.P. Quarry, Eugenana, looking south.

Width of foreground: two feet.

offset on a vertical shear (figure 21g). However, it is probable that the two sets of shears are essentially contemporaneous as they carry very similar lineation patterns.

The lineations on the oblique shears may be classed into three sets by orientation, the means of the sets pitching 20N, 60N and 30S, in the shear plane. Not as well defined as these are three sets on the vertical shears, pitching 20N, 60N and 20S.

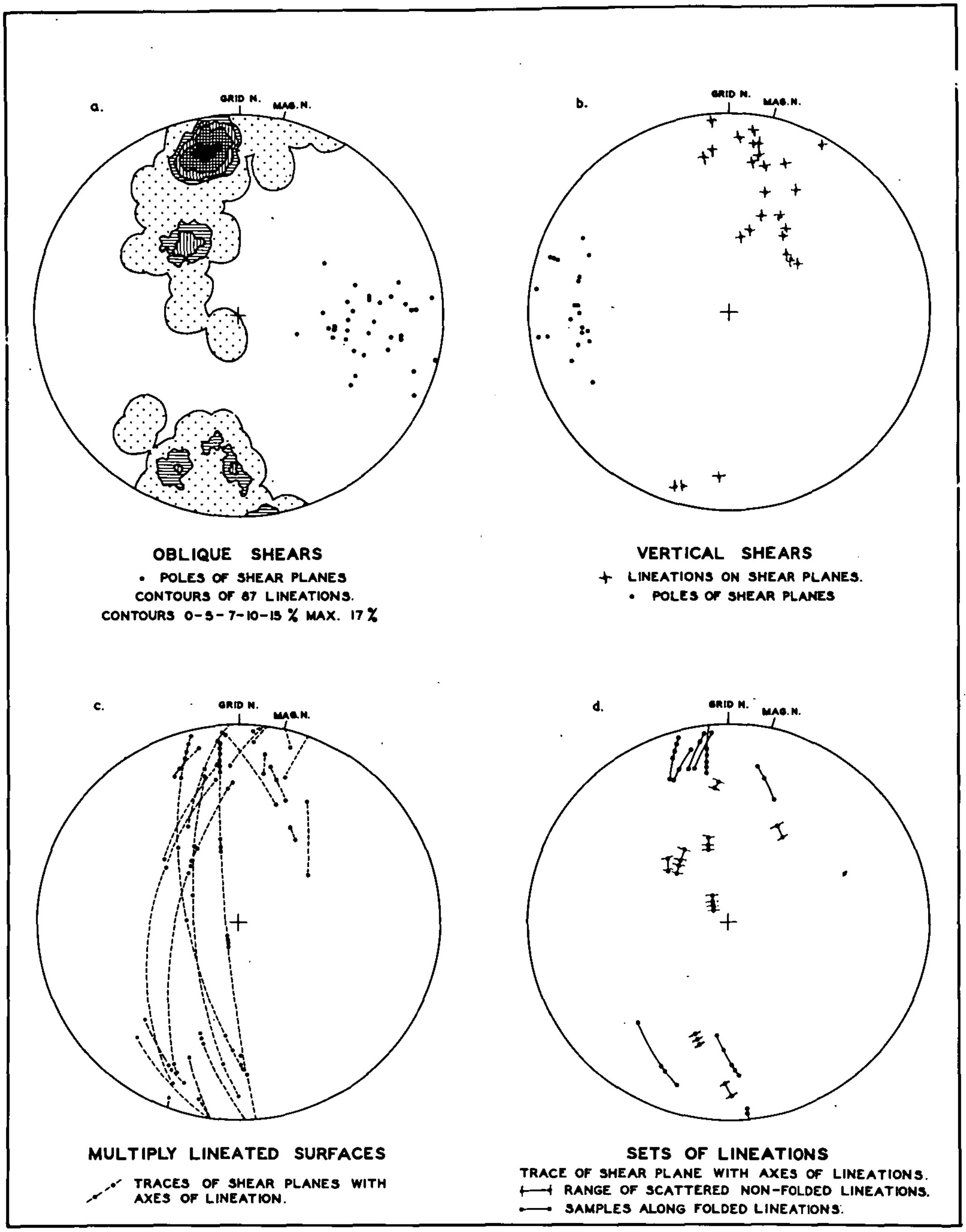
This division of the lineations into groups can be sustained for lineations on a single shear surface. Figure 22c is a plot of multiply lineated surfaces and it shows that three sets occur on a single surface. It is likely that all the shear surfaces are multiply lineated.

The lineation was measured as pitches in the shear surface and only lineations in recrystallised calcite were measured. On some shear planes the calcite mylonite is thin, and the trace of the foliation is a prominent lineation. This lineation is readily identified and was avoided.

Many of the measurements made on the shears were repetitive, thus in a typical example, the measurements were 15N, 15N, 75N, 12N, 14N, 70N, 15N, 16N, 72N, indicating two sets, of mean pitches 15N and 72N. It was possible to trace single sets of lineations through curves on the shear surface. For example, in a shear surface dipping 70SW335, one set varies from a pitch of 15N, through 5N to 38S; and another set from 28S through 30S to 45S; as continuous, uninterrupted curves on the planar shear surface. The curved sets can be differentiated from others by this continuity through the range of variation, and by the considerably greater range (figure 22d). However, there could be more curved sets present than were identified.

It is probable that the curved sets are originally straight lineations which have been folded during reworking of the shears. Burns (1957b) has described a younger set of lineations crossing an older set, with curving and offsetting of the older set, in Ordovician quartzite. Ramsay (1960, p.80) has described curved lineations due to folding.

On some shear surfaces it is possible to deduce an order of formation of the lineations. In some cases, the curved sets are crossed by uncurved sets, so that if the curvature is superimposed, the uncurved set is the younger. Sometimes the pattern has the form of drag of the curved set in zones, between which the uncurved set is well developed. In other cases one set of lineations which outcrop as distinct corrugations is crossed by another set,



Shears of the second generation of folding
Eugenana

Figure 22

which chops little notches in the top of the corrugations, the notches lining up in the direction of the younger set.

On the basis that the curved sets are folded and are older than the uncurved sets, it is possible to deduce an order of formation. Figure 22d shows that the striations pitching about 20N and 30S are folded while the 60N set is unfolded. Thus the 60N set is younger.

For the oblique shears the order of formation of lineations was 20N, 30S, 60N. On the vertical shears, the 20N set was the earliest and from analogy with the oblique shears, the probable order was 20N, 30S, 60N. The set of lineations at 60N agrees in orientation with the striation on the foliation which pitches at right angles to the fold axes.

On three of the oblique shears, the 20N class consists of large, corrugated, cylindrical "humps" of calcite. On some shears the 20N class matches the trace of the foliation on the shear surface. The lineation is considered to be a mullion-like structure formed at the intersection of surfaces and athwart the direction of movement in the shear surface.

Mullion structure is formed when there is simultaneous movement on two intersecting surfaces. Plate 16 shows a calcite seam, probably mylonite on an early oblique shear surface, which has been offset by movement on the foliation, with a new oblique shear developed immediately below. The movements occurred on, first, the old shear; second, the foliation; third, on another shear; that is, movement on the shears and the foliation was essentially contemporaneous. One of the mullions is crossed at a high angle by a younger lineation of the 70N class, the latter "knicking" the corrugations of the former. It is likely that the 30S class is also a mullion structure.

In summary, it appears that on the oblique shears there is a mullion-type lineation pitching between 20N and 30S parallel to the fold axes, which was developed athwart the translation direction on the shears, parallel to the kinematic 'b' axis. The mullions are refolded, hence the range of pitch, by a second lineation (a grooving) parallel to the 'a' direction of movement on the shear.

Third Generation Folding: Folds of conjugate profile occur in Rundles Quarry. They refold the foliation, so are younger than the first generation folds. The axes and axial planes are oriented (figure 23) at large angles to those of the second generation folds.

The folds are open, and rounded, with conjugate profile but without axial shears. This is in contrast to the second generation folding in which shears are well developed and the conjugate profile is rare.

The style and orientation mark these folds as of a

THIRD GENERATION FOLDING

EUGENANA

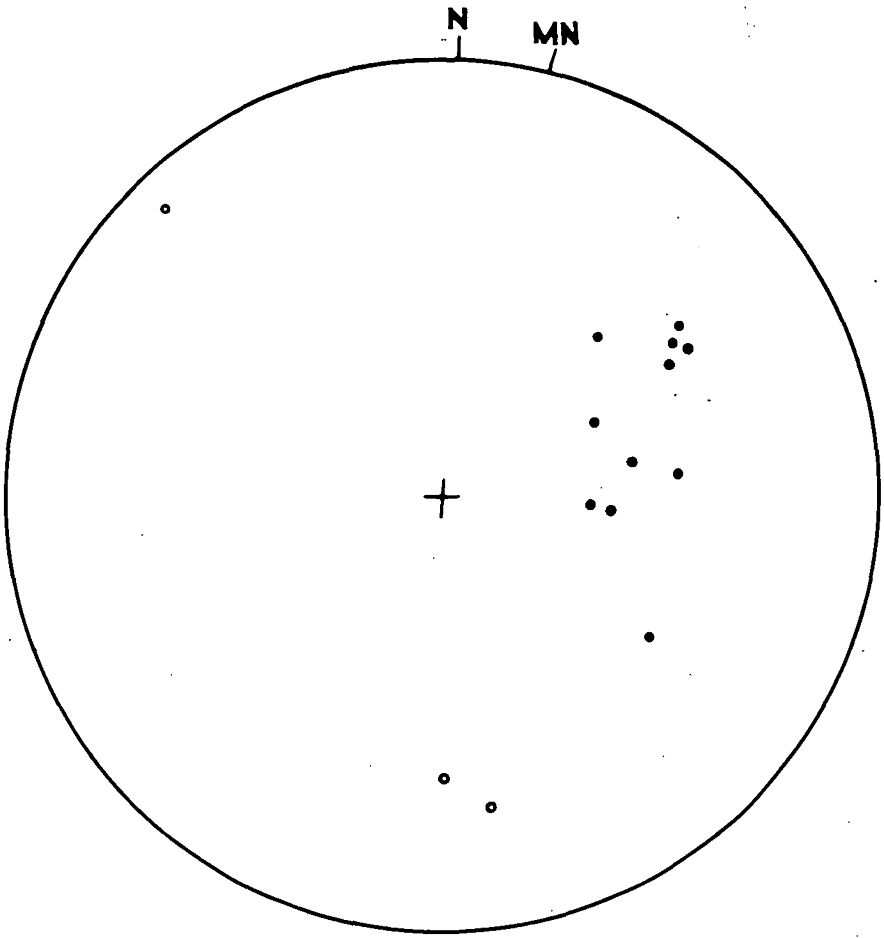


Figure 23

new generation. They post-date the folds of the first generation and have axes oriented differently to the axes of the first and second generation folds. It is likely that they were formed in a third movement period so they will be termed "third generation folds".

Conclusions: The second generation folding developed by non-affine reworking of the foliation formed in the first generation.

The folds are oblique-shear type, with rare conjugate styles. The axial surfaces pass downward and upward (usually only downward) into "knick planes" which curve co-axially with the folds.

Since the axial surfaces of some folds are cross-cut by oblique shears, some folding precedes the oblique shearing (figure 21k). Since some calcite veins parallel to oblique shears, and probably representing early oblique shears, are "stepped" by movement on the foliation (plate 16), some folding post-dates the oblique shearing. Thus the phases of folding and shearing overlap and are essentially contemporaneous.

The vertical shears have a similar lineation pattern to oblique shears, and probably were formed at the same time.

Contemporaneous translation on the oblique shear planes and slip along the foliation caused the formation of calcite mullions in the mylonite of the oblique shear surfaces. Continued movement on the oblique shears folded the mullions and generated a set of groovings parallel to the translation direction on the surfaces. This later striating could be Devonian, as is the folding, or Tertiary.

The first generation folding pitches 25 degrees south in a foliation striking near 180. The second generation folding plunges near 0-180. The two generations are considered to be successive episodes in a single movement phase. The differences in style are changes in manner of deformation, probably due to a change in the rate of strain. At low strain rates, the limestone will yield plastically, but at high rates of strain a more brittle deformation occurs.

The first movement phase is named the "Eugenanan". This name is introduced in place of the usual term "north-west trending folding" to simplify discussion. In addition, I.B. Jennings has shown (pers. comm.) that folds of this movement phase can be traced in a wide arc across the north of Tasmania, the trend varying through an arc of forty-five degrees, so that the directional term "north-west" is not always accurate.

The third generation of folding is thought to represent a second movement phase, which is also widespread on the North Coast. The name of "Loonganan movement" is given to this phase, as folds of this phase are best developed at

Loongana (a map of the Loongana Syncline is given by Hughes, 1957, p.139 and is reproduced here in figure 33). The trend of the Looganan folds is 240 at Eugenana.

Sulphur Creek

<u>Introduction</u>: On the headland at Sulphur Creek, the basement is Precambrian sandstone and mudstone of the Rocky Cape Group. The overlying rocks are conglomerates and sandstones of the Ordovician Dial Subgroup (figures 24 and 48).

The folds, representative of the folds usually encountered in the Junee Group, are open, with gently-dipping limbs, numerous thrusts and very few well-defined minor folds.

East of the headland, portions of three small basins are exposed. The periclinal structure of the basins is due to two periods of folding, about axes trending near south, and near south-west. An attempt is made to define these directions precisely, using three structural elements - bedding, faulting and jointing.

For convenience, the basins will be designated "east", "middle", and "west", as in figure 24.

<u>Faults</u>: The thrust faults in the conglomerate are identified as break thrusts, that is as thrusts formed synchronously with folding, for three reasons.

First, the faults curve within beds and at their terminations run along bedding, showing their movement is compatible with the bedding plane slip which occurs in flexural folding. Second, a few small disharmonic folds

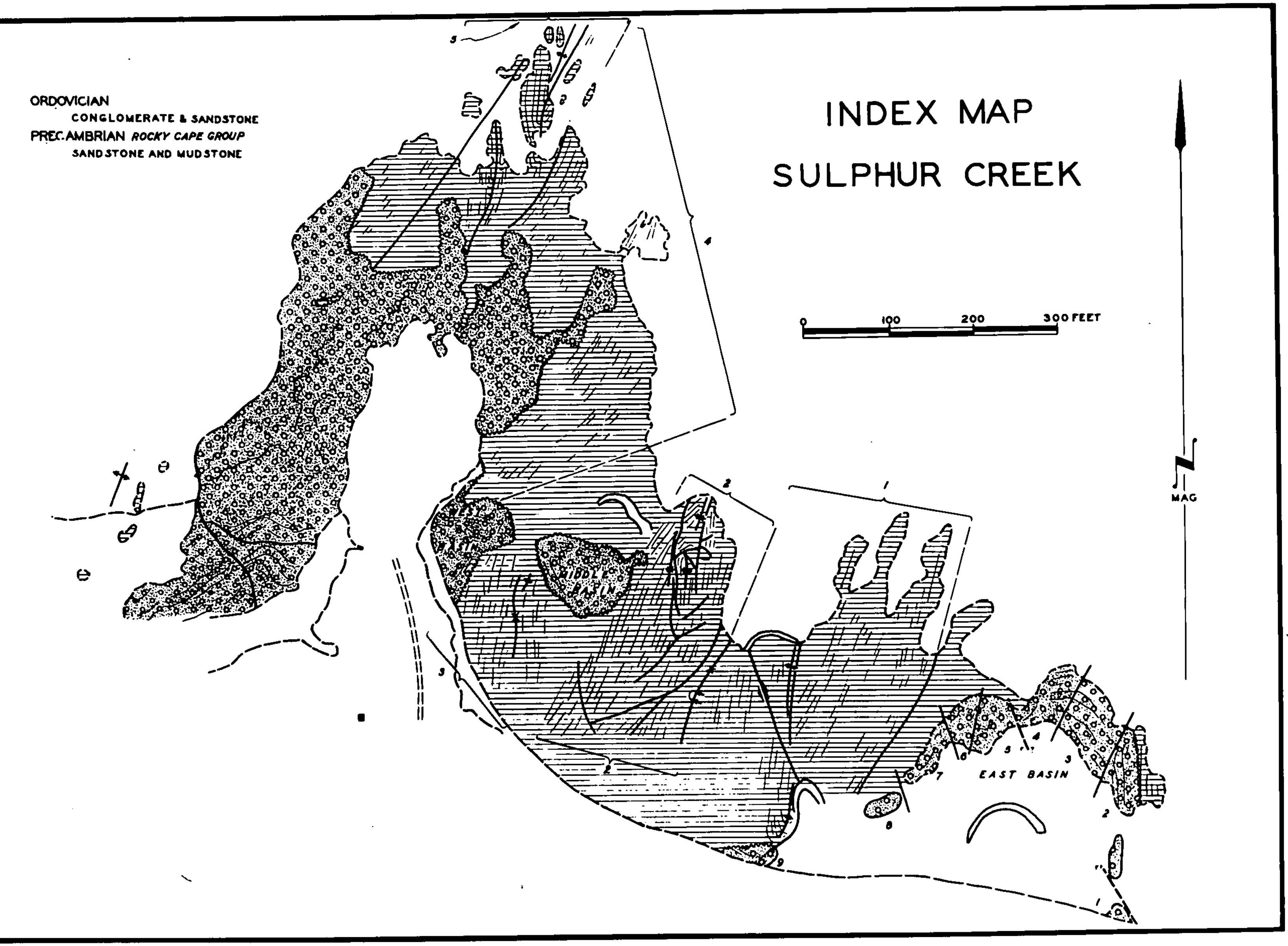

ORDOVICIAN
CONGLOMERATE & SANDSTONE
PREC.AMBRIAN ROCKY CAPE GROUP
SANDSTONE AND MUDSTONE
INDEX MAP
SULPHUR CREEK
0
100
200
300 FEET
MAG
MIDDLE BASIN
EAST BASIN

Figure 24

"ride" on the thrusts showing that folding accompanied faulting. Thirdly, in orientation and style they match no known post-Tabberabberan structures, but resemble strongly the synchronous break-thrusts in the Junee Group in other areas. In particular, the occurrence of two sets of common strike and opposing hades, is diagnostic (Jennings, 1958).

The observed faults are plotted in figure 25d. The mean strike is 340, with the 'b' axis of slip near 005. The faults intersect on the projection in a direction of azimuth 245, probably as a result of refolding.

The faults were formed with the 'b' axis at 340, that is, in the Eugenanan period of deformation, and may have been refolded in the Loonganan by an axis trending 245.

<u>Joints</u>: The conglomerate is graded, with fine grained (mudstone) tops which preserve excellent joints. The joints are regular in the mudstone, but weaken downwards to all but vanish in the conglomerate.

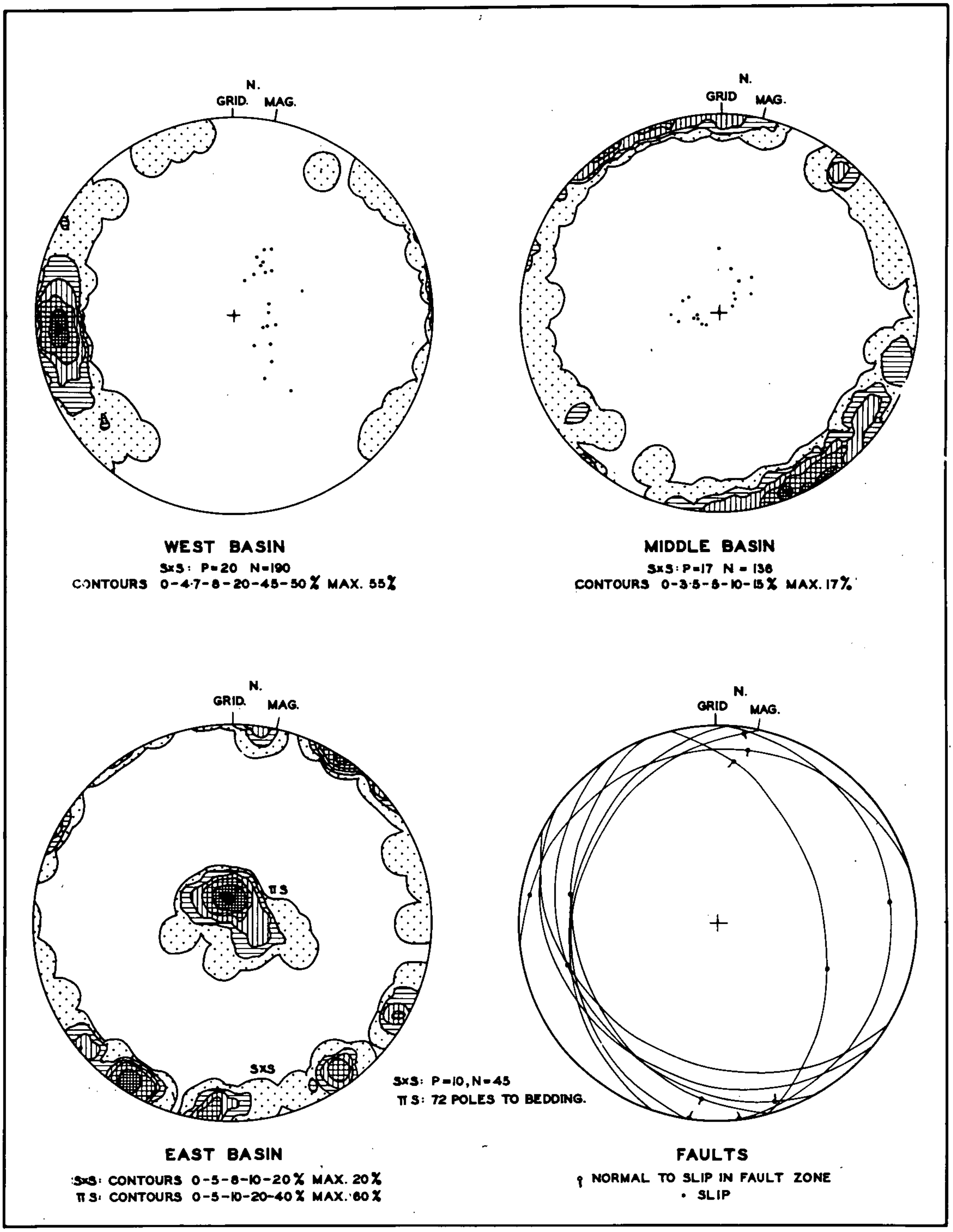
The joints were sampled in nine places around the rim of the east basin. In each locality the mean dip of bedding was determined, the mean dip of each joint set, and the mean direction of the acute bisectrix of the joint traces on bedding. Measurements in three localities are shown in figure 26a, b, c, and the mean A, B, C, axes for all nine localities are shown in figure 26d, the latter being computed after the method of Phillips (1954, pp. 24-27).

Several joint systems are present. However, attention was confined to a single system of conjugate shear joints which is readily identified. The style of the joint pattern varies, in some areas the two sets are equally developed, while in other areas one set is dominant and the other occurs as a set of weak, discontinuous fractures. One set has a uniform direction, striking 030 and dipping steeply northwest. The other set curves between 320 and 360, dipping steeply northeast in most cases, but sometimes dipping northwest. In any small area the curvature of strike is not noticeable.

To facilitate discussion, planes of joint set striking 030 and dipping steeply NW will be denoted J1. Planes of the set striking between 320 and 360 and dipping generally northeast will be denoted J2. Let S denote bedding, and A, B, C the principal axes of strain (after Phillips, loc. cit.)

The traces of the joints on bedding are then the lines J1xS, and J2xS. The direction bisecting the angle between these lines is plotted in figure 26 as the "acute bisectrix".

In each locality the plane bisecting the dihedral



Bedding and faults in Ordovician rock, Sulphur Creek.

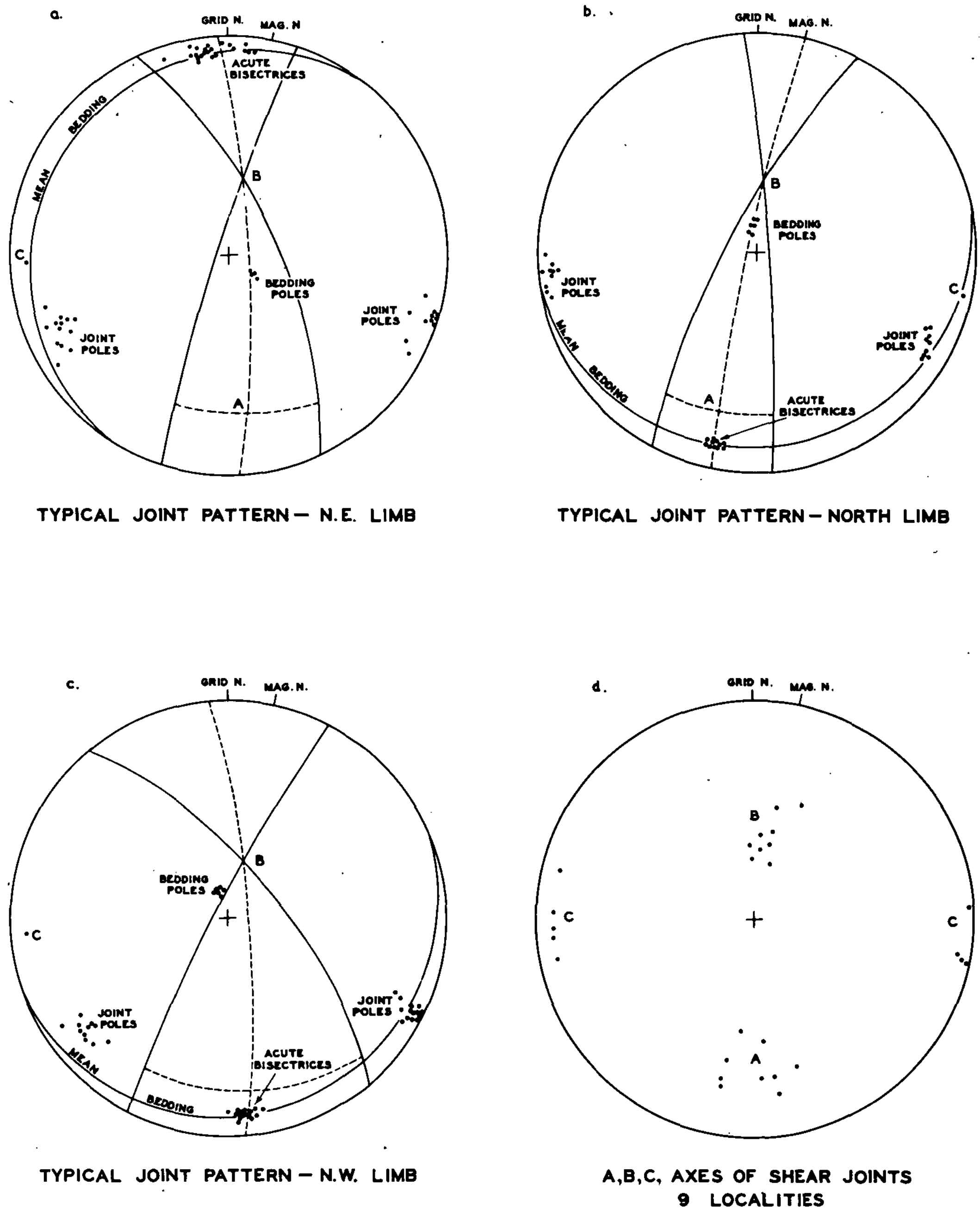
Figure 25

angle between J1 and J2 was computed as the plane 'AB' of figure 26. The trace of this plane on bedding is very close to the measured acute bisectrices discussed above. This concordance is not necessary on a priori grounds, and may be due largely to the very low dips of the bedding.

From the measured J1 and J2 planes, the directions A, B, C, were obtained. The mean A, for the nine localities, is near 30-180. The direction 'A' does not lie in bedding, but departs from it by twenty-five degrees. In one case 'A' plunges south when the bedding dips north. The dihedral angle between 'A' and the bedding has been determined. The angle is found to be ten degrees in the interior of the basin, where dips are gentle, increasing to twenty-one degrees at the northern rim, where dips are steep. Fragmentary contours of "equal dihedral angle" can be drawn on a map, and are found to outline a syncline elongated north-south.

The joints were therefore superimposed on already-folded beds, that is, the joints post-date the folding. The joints post-date the folding on the Eugenanan trend, but the relationship to the Loonganan folding is obscure. It is probable that the jointing predates the Loonganan folding.

In one locality, on the south-east limb of the east basin, slickensided joints displace a thrust fault. The joints are thus post-faulting.



Shear joints in Ordovician rocks, east basin, Sulphur Creek.

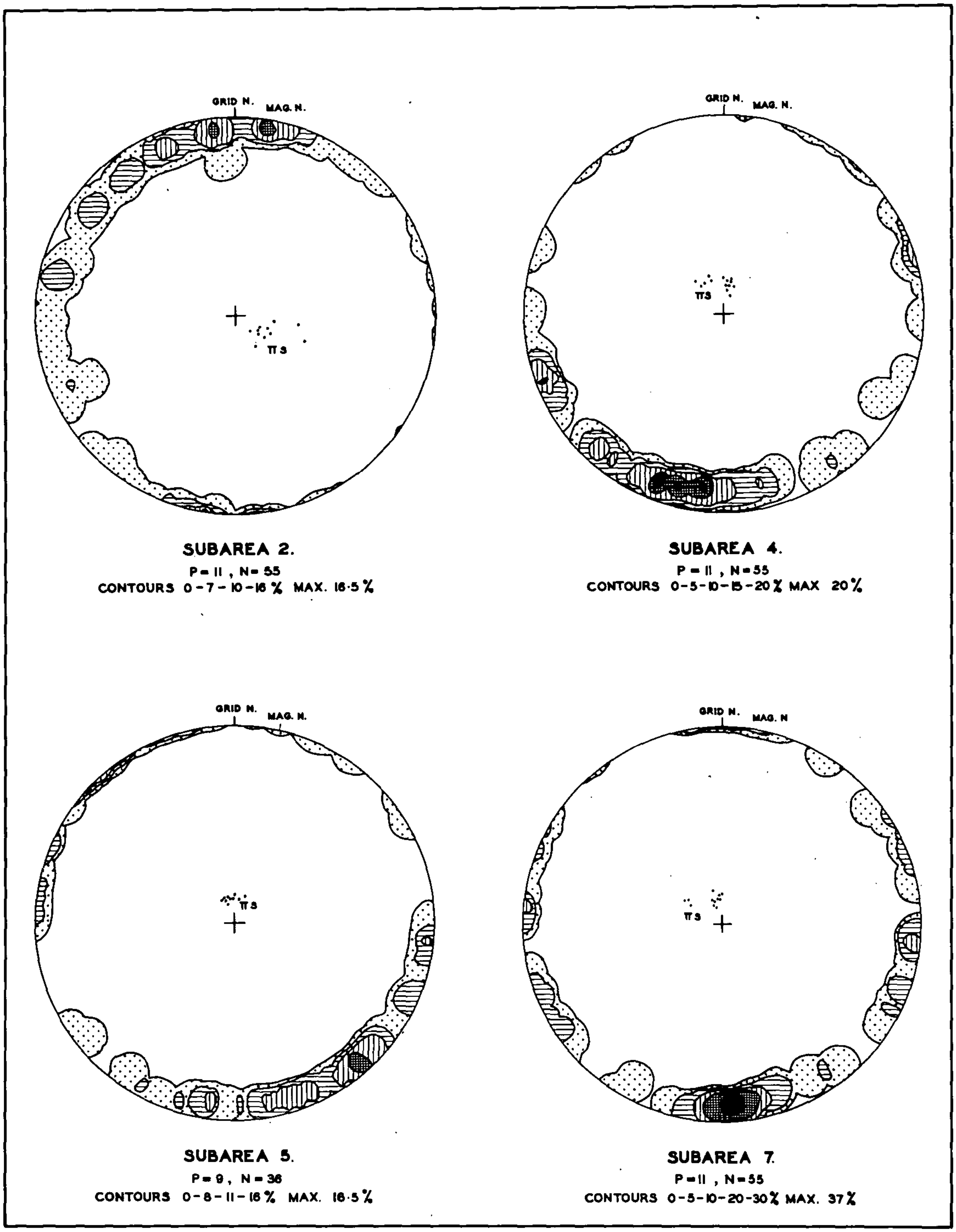
Figure 26

Bedding: Beta diagrams for the three basins east of the headland are shown in figure 25. In the east basin the dip was averaged for a number of subareas of the fold and the average dips were used. In the other basins the diagrams are constructed from all the measurements that were made.

All measurements were taken in mudstone or fine grained sandstone. In the latter, the strike was determined with a three foot clinometer and the dip measured with an abney level on a wooden staff laid in contact with the bed. The dips in sandstone are averages of areas three feet in diameter. In mudstone the measurements were made with a short clinometer and brunton compass. Precise measurements are possible of small elements of the bedding in mudstone but with the low dips the brunton alone is inadequate to properly determine the strike.

The west basin is an open fold with the axial plane dipping steeply north. A strong beta maximum is obtained. The middle and east basins are very shallow folds with vertical planes of symmetry. The beta diagrams yield girdles with a number of maxima.

The east basin was divided into a number of small subareas. Beta diagrams for four of these subareas are shown in figure 27. Insufficient measurements could be obtained in the other subareas to warrant reproduction.



Bedding in Ordovician rocks of the east basin, Sulphur Creek.

Figure 27

The diagrams again yield girdles with a number of maxima.

The results indicate that the folding is non-cylindrical. Even the small subareas of the east basin have two finite radii of curvature. This is a phenomenon visible in the field. Each outcrop of the bedding, where it is well defined as in mudstone, curves to follow the outcrop of the basin rim, and curves toward the basin centre. The curvature is noticeable with instruments longer than about twelve inches, which contact the bed in only two points and are not in contact with the bed for their full length.

As shown in Appendix 3, beta-maxima in non-cylindrical folds vary in size depending upon the position of the fold which is sampled. The largest maxima are obtained from traverses through the basin centre in directions parallel to the axes of basin symmetry.

In figure 28, beta maxima obtained from all diagrams prepared at Sulphur Creek are evaluated, by plotting the size against azimuth. The size is evaluated in two ways.

Let P be the number of bedding planes plotted on a beta diagram. Then if S denotes bedding, the number of SxS intersections is N, where

$$2N = P(P-1)$$

In practice, the SxS intersections were computed from a Wullf net, and transferred to a Lambert net for contouring.

A maximum in the contoured beta-diagrams represents the number n of SxS intersections lying within a one-percent area of the net centred on the maximum. Then the value of the maximum is

$$100n/N \text{ percent.}$$

These values are plotted against azimuth in the upper figure.

In order to compare results from a number of diagrams, the maxima must be evaluated in a different manner. This is done in terms of the "p-value". Since the number P of planes have $(P^2-P)/2$ intersections, then it can be shown that 'n' intersections represent 'p' planes, where

$$p = \frac{1 + \sqrt{8n + 1}}{2}$$

The quantity 'p', or P-value, is not necessarily an integer. This quantity properly evaluates the maxima. For example, a maximum representing six parallel planes crossed by a seventh has a p-value of 4, and a maximum formed by the simultaneous intersections of 6 planes has a p-value of 6, in each case regardless of the number of intersections in the remainder of the diagram.

In figure 28, maxima of low value have a random azimuth. Four maxima stand out from the rest, defining directions at 254 and 148. The first direction is the axis of symmetry of the west basin, the second is the axis of symmetry of the middle basin.

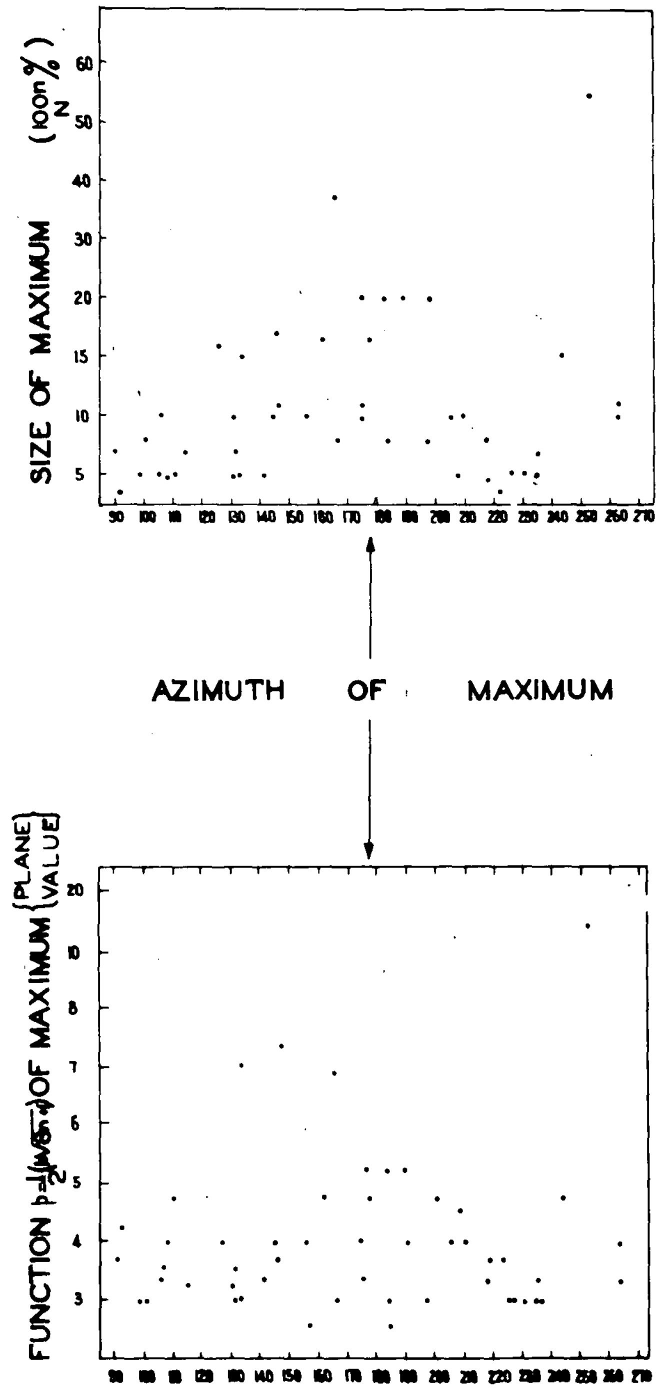

SIZE OF MAXIMUM (100n/N %)
AZIMUTH OF MAXIMUM
FUNCTION OF MAXIMUM (PLANE VALUE)

Figure 28

In view of the contention of Appendix 3 that the axes of basin symmetry are not necessarily parallel to the causative fold trends, these two directions of high beta-maxima are considered as of no significance in defining the fold trends. This evaluation runs counter to Lindstrom (1961). If the diagram for the whole of the east basin is considered (figure 25c) the poles of S form intersecting girdles with corresponding S x S maxima, which reflect only the basin shape. The maxima represent traverses along the north-west and east limb. The maximum with azimuth 180 bisects these limbs and from the hypothetical map of Appendix 3, is likely to represent a fold trend. The thrust faults indicate the same direction.

One fold trend is at 180, the other, from the east basin diagrams, must lie west of south-south-west. It is probably close to the direction of the maximum of the west basin but not necessarily parallel to it, as subareas Y and Z of Appendix 3 show that high maxima can be obtained up to thirty degrees away from the fold trend. From the evidence of other areas the second fold trend is probably near 250.

The trend at 180 is identified as the "Eugenanan", that near 254 as the "Loonganan". The thrust faults are Eugenanan while the shear joints are post-Eugenanan, and possibly pre-Loonganan.

The Dial Range

Introduction: The Ordovician rocks of the Dial Range have broad, open folds with upright or steeply dipping axial planes; limb dips not usually exceeding forty-five degrees; and large wavelengths of up to several miles.

Analysis of bedding orientation is of little assistance in defining the structure, therefore, in one place or another, attempts have been made to utilise shear joints, fault striae, the rare minor folds, and form surfaces. Applied by itself, each of these elements has grave limitations, but used in concert, a fairly coherent picture emerges.

Penguin: At the north end of the Dial Range is a shallow, faulted basin which runs under Penguin to Bass Strait. The dips vary from five to twenty-five degrees on the east limb, determined from direct measurement or from calculation of the trace of marker horizons on topography. Eleven such measurements from the eastern limb yield a beta plunging 10-247.

In the same area, a thrust fault passes through massive Duncan Conglomerate, the fault plane dipping 13E187. On entering the overlying bedded conglomerate, the fault is refracted to 25NE137, with striae plunging 16-098. The 'b' axis, at right angles to the slip in the fault plane, is 20-362.

A little further south, two intersecting thrusts dip 30W162 and 35W022, with subordinate crossfaults. The thrusts intersect in a line oriented 30-257, which in the main thrust is perpendicular to the direction 10-364.

The splayed and refracted thrusts have a symmetry about an azimuth near 360, which is, by inference, one of the principal axes of strain.

<u>Mt. Dial</u>: The Moina Sandstone capping Mt. Dial is folded into a very shallow syncline, with the trough line plunging north at 400 feet per mile. Hughes (1953) thought the axis had an azimuth of 020. This assertion was tested by construction of composite profiles of the type "senkrecht zur topographischen Ebene" of Wegmann (1929, pp.111-113). It was found that successive sections transverse to an azimuth of 020 could not be directly superimposed to give a consistent profile, and in fact they need to be offset by such amounts as to indicate that the direction of uniform profile is close to 360 (within ten degrees of 360). Thus, from analysis of the form surfaces, one axis of form-symmetry of the fold has an azimuth of 360.

Profiles normal to an azimuth of 360 are shown in figure 29. There is a change in profile at the western side of the Range due to the stratigraphic thinning of the Duncan Conglomerate. If allowance is made for the very high original dips in the Duncan fanglomerate it is found that rather than being a syncline Mt. Dial is folded into a gentle anticline. The fold in the overlying sandstone is merely a reflection of changes in thickness of the conglomerate.

It is likely that the unconformity at the base of the Duncan Conglomerate is occupied by a large flat-lying fault, but there is no direct evidence of this in the Ordovician rocks.

<u>The Gnomon</u>: The south face of the Gnomon is the movement surface of the Dial Fault. Mapping shows the fault strikes at 300, is vertical, and the principal component of movement is a dextral strike-slip.

A number of minor faults are exposed in the cliff face. A dextral transcurrent fault dipping 87N309 is parallel to the major fault, and a sinistral transcurrent fault dipping 84E357 is probably a second order shear (McKinstry, 1953). The "R" axis of stress (Anderson, 1951) plunges 5-230, but this indicates only the local stress field on the north wall of the fault and is of no regional significance.

There is a second group of minor faults, dipping between fifty-six and seventy-two degrees to the northeast. The faults are oblique-slip, the striae pitching 70W in the fault dipping 56NE332; and pitching 7E in a fault dipping 72N287. Between the extremes there is a range of dips

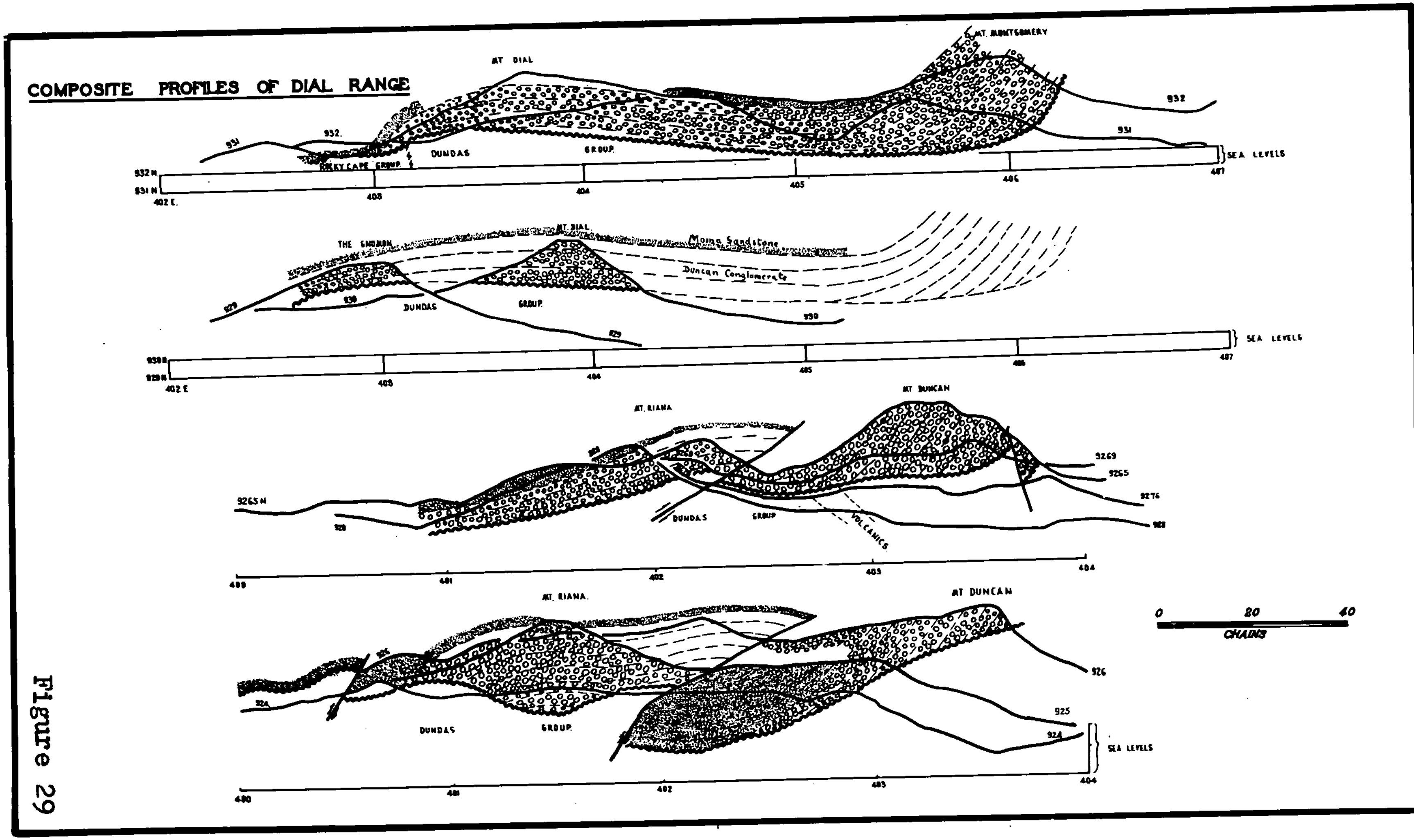

COMPOSITE PROFILES OF DIAL RANGE
MT DIAL
MT. MONTGOMERY
931
932.
DUNDAS
GROUP
ROCKY CAPE GROUP
932
931
SEA LEVELS
932 N
931 N
402 E.
403
404
405
406
407
THE GNOMON
MT. DIAL
Moina Sandstone
Duncan Conglomerate
929
930
DUNDAS
GROUP
930
929
SEA LEVELS
930 N
929 N
402 E
403
404
405
406
407
MT. RIANA
MT DUNCAN
9265 N
9269
9265
9276
DUNDAS
GROUP
VOLCANICS
400
401
402
403
404
MT. RIANA.
MT DUNCAN
0
20
40
CHAINS
926
926
925
924
924
DUNDAS
GROUP.
SEA LEVELS
400
401
402
403
404

Figure 29

and pitches that appear to be in continuous progression. A third group of faults is represented by a thrust dipping 26NW045, the striae pitching down-dip.

This collection of faults cannot be explained as subsidiary faults (McKinstry, 1953; Moody and Hill, 1956) developed in a single stress system; nor as faults developed in a rotating stress system (Williams, 1958). Rather, there must be at least two episodes of faulting.

The major fault plane outcrops as a smooth, polished face about 100 feet high, bounded by crush breccia. The transcurrent faults produced the crush breccia, and the minor faults occur in the crush breccia. The succession indicated is north-west striking major transcurrent faulting followed by north-east dipping minor thrusts.

Mt. Duncan: The southern part of the Dial Range, from Mt. Duncan south to the north end of Gunns Plains, is strongly crossfolded. The composite profiles of figure 29 show a marked contrast between this area and the Mt. Dial area further north. The change in profile is located at the Dial Fault.

The dominating feature of the southern area is the Duncan Fault. At Mt. Duncan, and for two miles to the south, this is a thrust dipping twenty-five degrees west, with a stratigraphic throw varying along the fault from zero to 1200 feet, measured on the top of the Duncan

Conglomerate. The slip is, however, uniform and reaches a maximum of 1000 feet.

The fault strike averages 180, a thick tongue of fanglomerate running from Mt. Duncan to the south end of Mt. Dial strikes 220. The oblique intersection of the tongue and the fault is responsible for the variable stratigraphic throw.

The fault is a strike fault, dipping steeper than bedding and hence repeating the succession at the south end of the Dial Range. The fault plane is occupied by a small neck of quartz dolerite, probably of Devonian age.

North of Mt. Duncan the fault follows the unconformity at the base of the Ordovician, and may terminate on the Dial Fault. However, mapping of the Cambrian indicates that the Dial Faults do not continue through the Cambrian, being confined to the Ordovician rocks above. It is therefore possible that the Duncan Fault continues north of the Dial Fault as a flat thrust at the base of the Duncan Conglomerate.

South of Mt. Duncan, the Duncan Fault swings sharply southeast around the nose of Mt. Lorymer, to link up with the Walloa Creek Fault (figure 30). The Walloa Creek Fault has a vertical fault plane.

There are three alternative explanations for this arrangement of faults. The dip of the Duncan Fault surface could vary along the strike with the apparent reversal of throw a primary feature. Alternatively, the steep part of the fault may have been reworked. The third alternative is that the fault was of near constant dip and is offset by the Walloa Creek Fault.

At a later stage, evidence will be presented of the existence of low angle faults in the Cambrian and Ordovician rocks of the Leven Gorge. These are identified with the Duncan Fault, supporting the third alternative.

The character of the Duncan Fault varies along its strike. North of Mt. Duncan it follows the base of the Ordovician; two miles south of Mt. Duncan it has climbed up 2000 feet into the succession; at Mt. Lorymer it has dropped to less than 100 feet above the base of the Ordivician, and in the Sugarloaf Gorge the principal movement is on surfaces within the Cambrian. At the south-east end of the Gunns Plains Basin (figure 33) it has climbed back up about 200 feet into the Ordovician.

These observations refer to the modern fault trace. However, the variations indicate rather more than simply the depth of erosion. For instance, the trace of the fault on topography is nearly horizontal for three miles south of Mt. Duncan, yet the height of the fault trace in the succession varies through 1200 feet. This variation implies one of two alternatives. The fault may have been formed with constant position in a fold profile (of the type

CONTOURS ON BASE OF MOINA SANDSTONE — DIAL RANGE

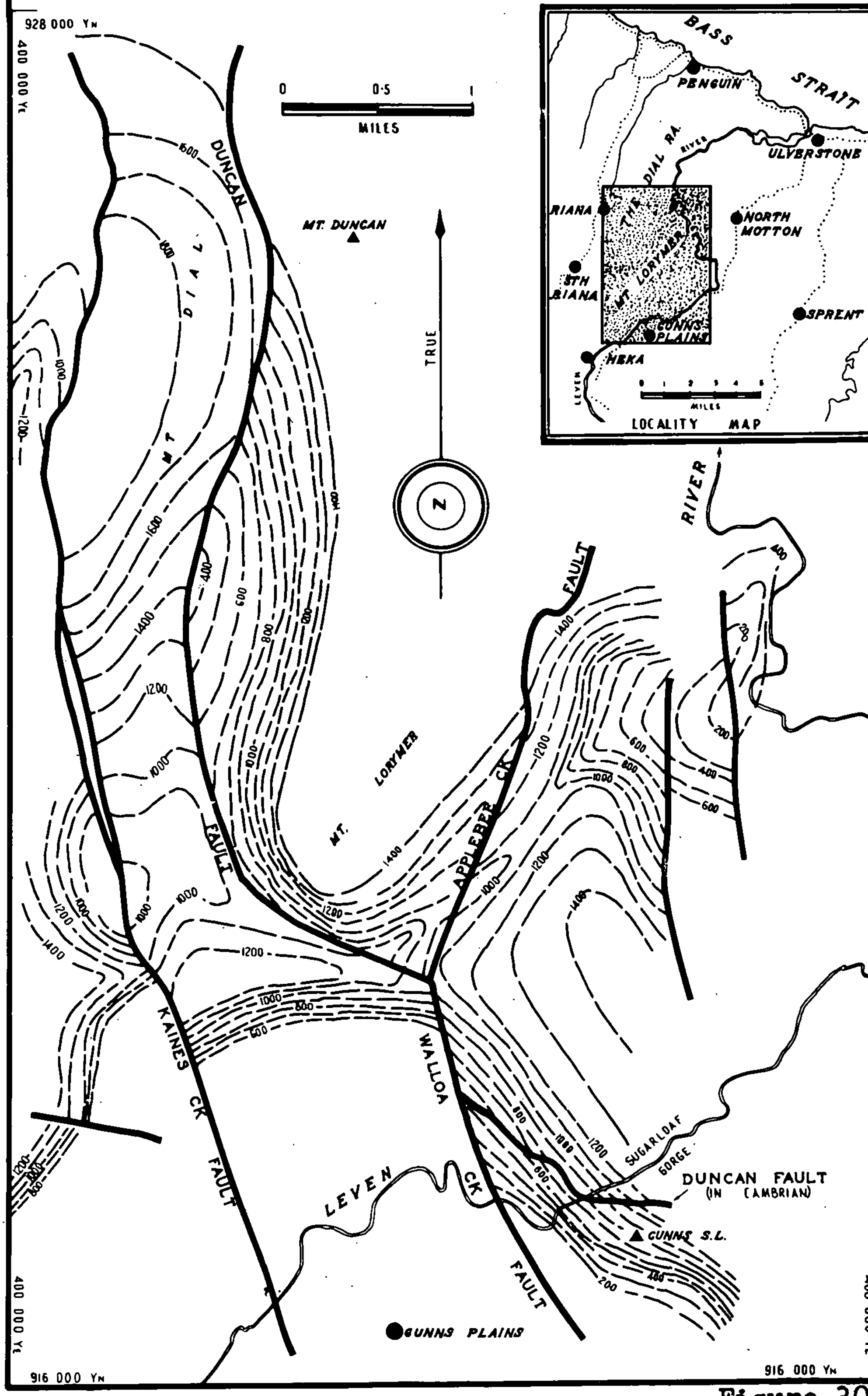


Figure 30

"senkrecht zur Axialrichtung" of Wegmann, 1929, pp.107-8) and the profile has been strongly refolded. Alternatively, the fault may have been formed with undulations co-axial to the slip, or has been developed as a planar structure on folded terrain, in which case there has been no refolding.

The reason for adopting the first alternative of folding post-dating the Duncan Fault is that this alternative provides the simplest solution consistent with the data available concerning not only the Duncan Fault but also faults in the vicinity which are related to it. This is not by any means a conclusive method of analysis.

The Kaines Creek Fault is well exposed in Pine Creek, north of the Leven River. The fault plane dips 80W187, with very well developed striae which are all exactly horizontal. The transcurrent movement explains the existence of the fault sliver a little further north. The fault has dextral strike-slip.

The Walloa Creek Fault, immediately west of its junction with the Applebee Fault, has a surface dipping 80S342 with strike pitching 20W throughout the wide crush zone. The major component of movement is thus dextral strike slip. The movement may be accommodated to the north by strike-slip movement on the Duncan Fault, but it appears that much of it is dissipated in a tight fold south-west of Mt.

Lorymer, indicated in figure 30 by the closed 1200 foot contour. If so, this implies that the Walloa Creek Fault was contemporaneous with folding.

In figures 30, 33, the Walloa Creek Fault is shown crossing the Gunns Plains Basin with little variation in attitude. The net stratigraphic throw on the fault is west side down. This throw can be reconciled with the slip in only one way, by inferring that the fault movement was contemporaneous with folding on a SW-trending axis. That is, there was differential folding in the sense of Rod (1959).

Adopting the simplest overall solution, the evolution of this structure is as shown in figure 31. The initial stage was folding about northerly axes, with development of the Duncan Fault at a constant position in the axial profile, as in figure 29. This was followed by rotation on south-west axes, establishing at any given horizon the oblique profile shown in figure 31, phase 1. This folding continued with development of the Lorymer Anticline and other cross-structures of phase 2. The end stage of the crossfolding produced the strike-slip faults trending west of north, with the folding being "differential folding" controlled by these faults.

EVOLUTION OF THE DUNCAN FAULT

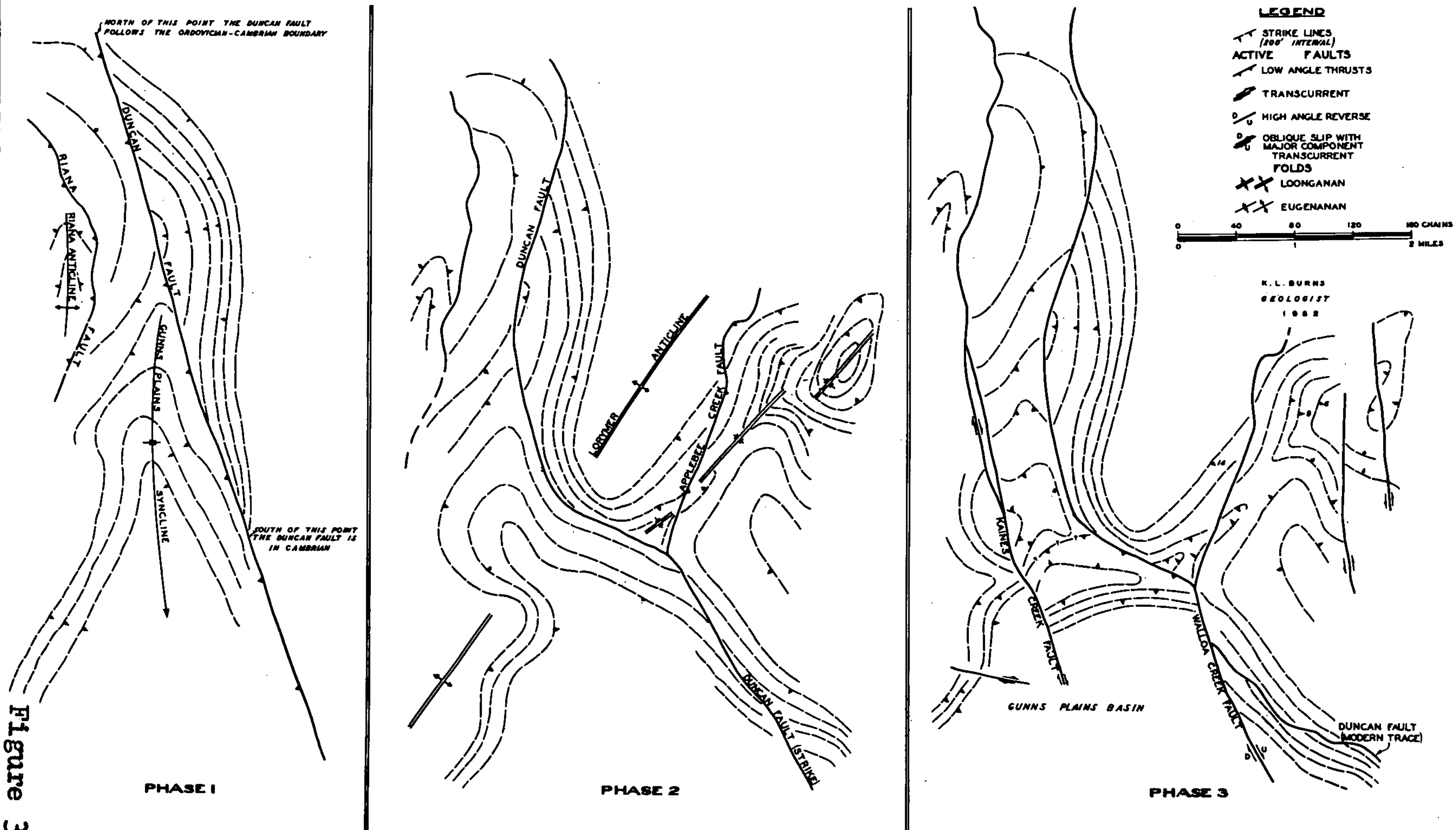


Figure 31

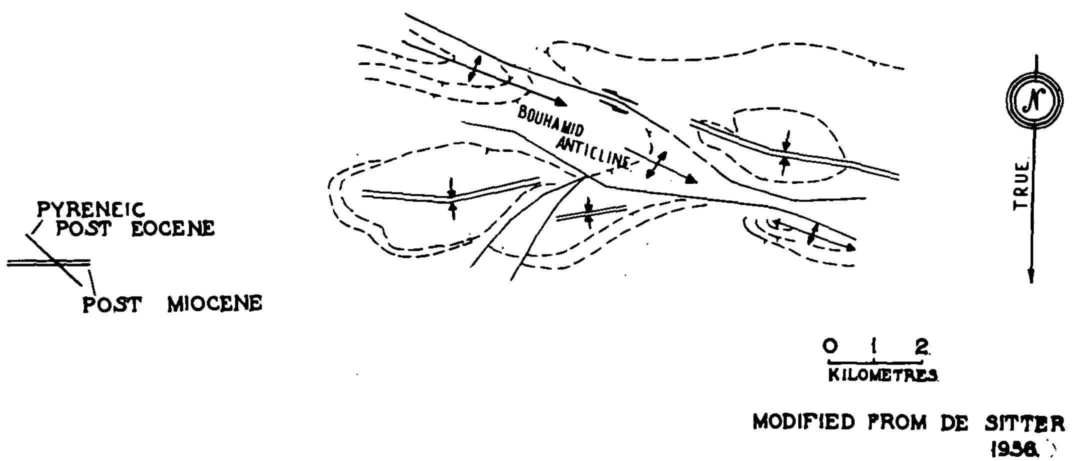
Northern Tasmania

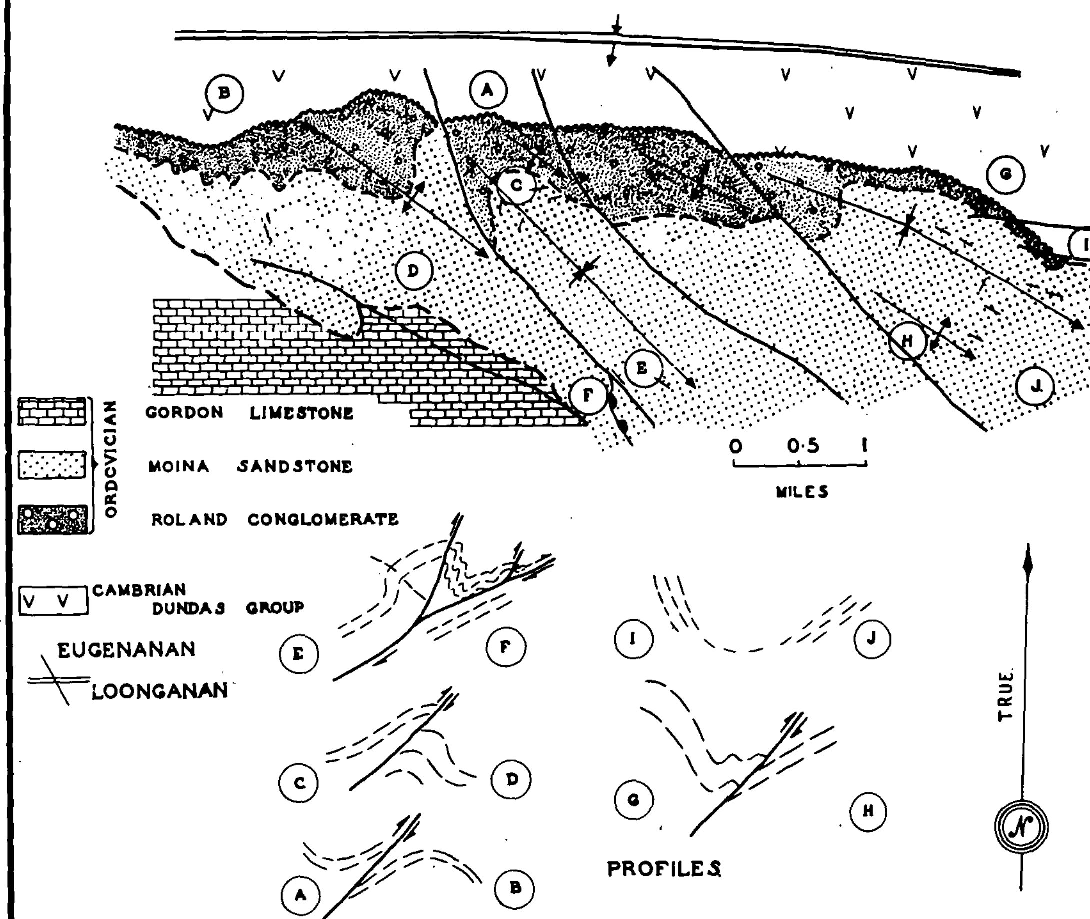
It has been shown that the structure of the Dial Range is consistent with superposition of folds on south-west trends on folds of north-west trends. In this section structures from elsewhere on the North Coast will be examined, by comparison of their "form-pattern" with established analogues.

The Gunns Plains Basin is shown in figures 30 and 33. North of Gunns Plains township, the limestone contains numbers of minor folds of about four feet amplitude with an axial strain-slip cleavage (in the sense of Knill 1960, p.322). The mean plunge of the fold axes and traces of cleavage on bedding is 25-172. South-east of Warringa a minor fold of some 400 feet wavelength in conglomerate plunges 17-345, parallel to the trace of cleavage on bedding in underlying Cambrian rocks. It is likely that these folds are not super-imposed but refolded. The folding of the basin is the product of superposed folding on axes shown in figure 33 with the Walloa and Kaines Creek Faults pene-contemporaneous with the second folding.

On the Gog Range the pattern of crossfolding, shown in figure 32, is analogous with de Sitter's High Atlas type. The folds trending south-east have plunges controlled by the superposed east-west monocline.

CROSS FOLDING IN THE HIGH ATLAS





CROSS FOLDING IN THE GOG RANGE

Figure 32

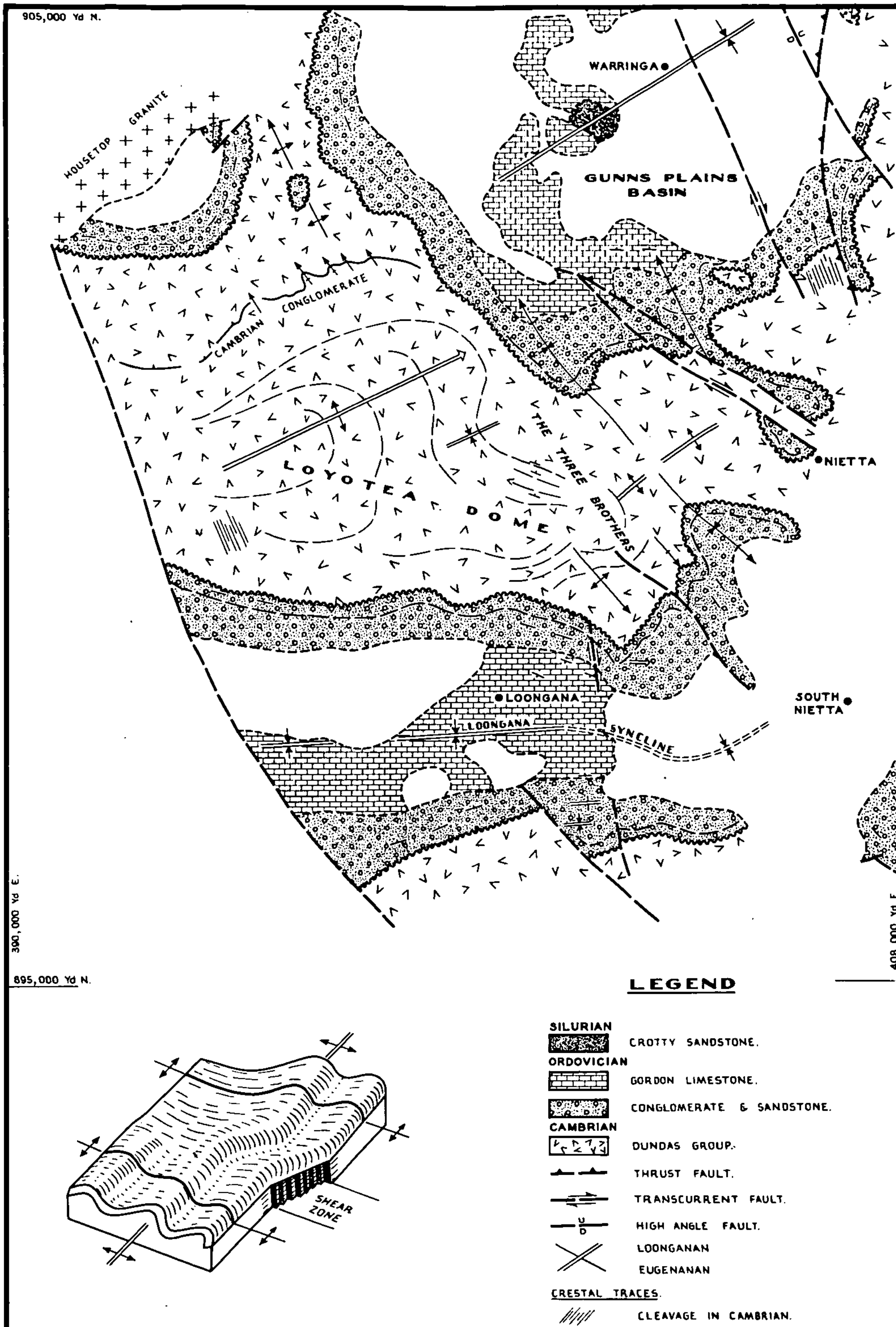
AFTER JENNINGS & BURNS 1958

Bradley (1956, p.77) has found a similar superposition pattern on Tasmania's West Coast.

The Loyotea Dome is shown in figure 33. The Loogana Syncline contains cylindrical minor folds on two trends, the east-west trend being well developed, as described by Hughes (1957, fig. 20). (However, folds with north-west axes have been observed at the western end of the syncline and on Black Bluff). At the western end of the dome there is a very strong cleavage developed in the Cambrian rocks, with minor folds plunging north-west, as indicated by folded Cambrian conglomerate. The dome is thus doubly folded. The internal structure is indicated by strike-lines from mapping by R.G. Robinson (Jennings et al, 1959).

There is an offsetting or discontinuity in the crestal traces of the dome. The Loonganan folds change profile in a zone trending north-west through the Three Brothers. This change in profile is probably due to differential folding, in the sense of Rod (1959). However, here the term "differential crossfolding" is applicable. Instead of the change in profile being across a narrowly defined fracture surface, the change is a gradual one, across a zone. This suggests the controlling inhomogeneity is at depth (cf. Carey, 1953, p.1126).

Superposed folds similar to these examples are wide-



DIFFERENTIAL CROSSFOLDING AT LOYOTEA

0 1 2 3 MLS.

Figure 33

AFTER HUGHES (1957), JENNINGS (1959)

spread on the North Coast of Tasmania and are consistent with a Eugenanan phase, developing folds and faults trending between west and north, followed by a Loonganan phase, with folds trending between west and southwest. Profiles of the second phase are discontinuous because much of the crossfolding is of a "differential" type, controlled by inhomogeneities developed in the first phase.

CHAPTER 7

STRUCTURES IN CAMBRIAN ROCKS

CHAPTER 7

Structures in Cambrian Rocks

Paloona

Eight miles southwest of Eugenana, in the vicinity of the junction of the Forth and Wilmot Rivers, there is a regular series of open folds which plunge southeast. (Jennings et al, 1959; and figure 16).

A small fold at Paloona Bridge has a beta maximum at 35-125 and a wavelength of 600 feet. Adjoining this on the south is a faulted anticline of about one half-mile wave-length. South of this is the Alma Syncline, a broad open structure in Barrington Chert which plunges 25-135 and has a wavelength of nearly two miles. Further south again, about four miles southwest of Paloona Bridge, there is a large, broad anticline, the Wilmot Anticline, of two miles wavelength.

The folds are simple, without minor folds and with uniform profiles. Outliers of Moina Sandstone are folded in accordance with the Cambrian, so the folding is Tabberabberan.

Several break-thrusts occupy constant positions in the axial profile, in one place thrusting Cambrian over Ordovician. The largest of these, on the south limb of the Alma Syncline, has a stratigraphic throw of the order of 3000 feet. One vertical fault with dextral strike-slip strikes close to 180. To the southeast the thrusts pass into, or are

GEOLOGY OF WILSONIA AREA

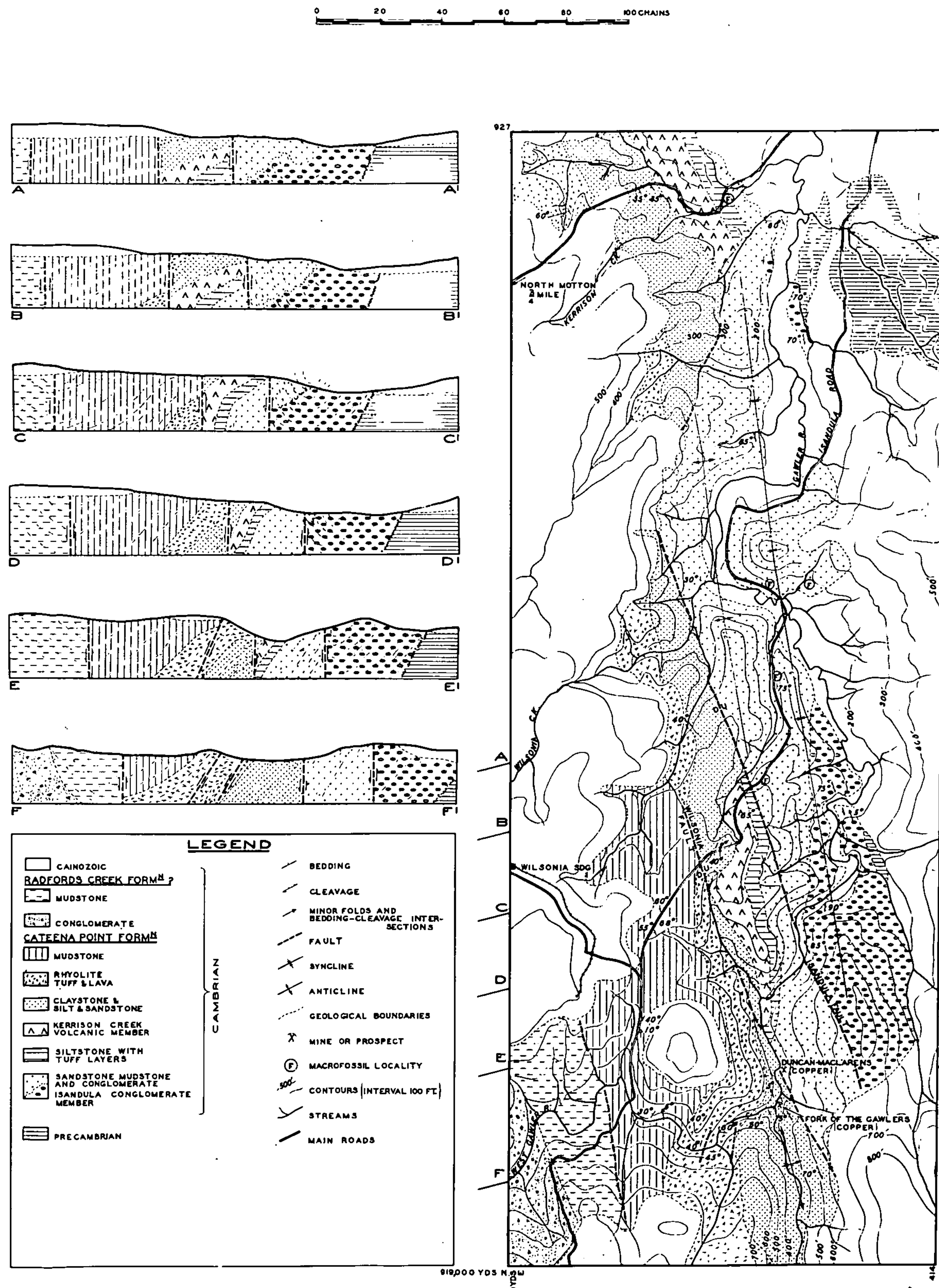


Figure 34

offset by, strike-slip faults of this type.

The regular increase in fold wavelength to the south reflects a basement deepening south. Reconstructions by Burns (1957) showed the folds could be concentric down to a level dipping twenty-two degrees south from Paloona Bridge, below this the folds can no longer be concentric.

At Paloona Bridge the folds are concentric without slaty cleavage down to the level of the top of the Precambrian which is here a graphite schist. It is likely that the change of fold style is abrupt and coincides with the top of the basement and that a decollement structure exists in this vicinity.

It has been calculated from measurement of the length of the folded area between Paloona Bridge and the Wilmot Anticline (method of Chamberlin, 1910), that the overall shortening is fifteen percent.

<u>Wilsonia</u>

The Wilsonia Area is between four and five miles south of Ulverstone (figure 34). The folds are tight, almost carinate, with a strong and widespread slaty cleavage.

Figure 35 shows a small, representative portion of this area. Contours of 362 bedding intersections from this area yield a sixteen percent maximum plunging 12-357.

Cleavage-bedding intersections from a number of localities in the Gawler River, one mile south of the Isandula Road

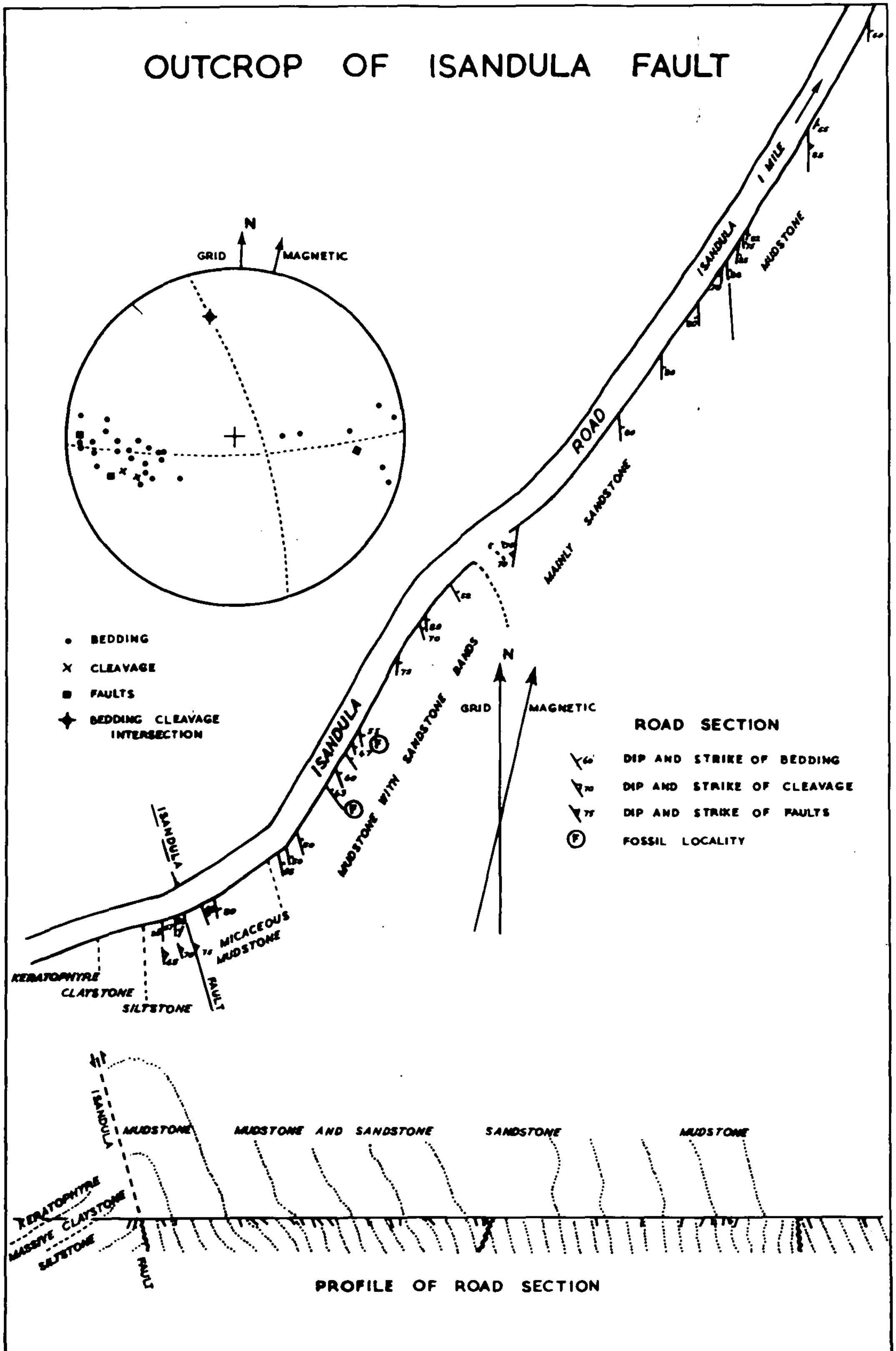

OUTCROP OF ISANDULA FAULT
N
GRID
MAGNETIC
BEDDING
CLEAVAGE
FAULTS
BEDDING CLEAVAGE INTERSECTION
ROAD SECTION
DIP AND STRIKE OF BEDDING
DIP AND STRIKE OF CLEAVAGE
DIP AND STRIKE OF FAULTS
FOSSIL LOCALITY
ISANDULA ROAD
1 MILE
MUDSTONE
MAINLY SANDSTONE
MUDSTONE WITH SANDSTONE BANDS
MICACEOUS MUDSTONE
FAULT
KERATOPHYRE
CLAYSTONE
SILTSTONE
MUDSTONE
MUDSTONE AND SANDSTONE
SANDSTONE
MUDSTONE
MASSIVE CLAYSTONE
PROFILE OF ROAD SECTION

Figure 35

section, fall close to this beta maximum. The plunge is maintained through a wide area in this vicinity, with the trace of cleavage pitching about ten degrees away from the strike. It is probable that the plunge is superimposed on a regional dip.

Two large faults cross this area, the Isandula and Wilsonia Faults. The faults are high angle reverse faults, dipping 75E340, with a total stratigraphic throw of about 1200 feet, west side down. The faults are parallel to the slaty cleavage, and presumably the same age. It is likely that the faults are continuous with the large thrusts of the Alma Syncline.

In this area the folds are tight, appressed, with slaty cleavage widespread. Axial planes are near vertical and faults are high angle reverse. The basement dips steeply, and approaching the basement, dips in the mantle become 75 degrees or steeper. The basement may have acted as a "buttress" with the mantle squeezed up against it during folding.

Ulverstone

Introduction: At West Ulverstone, near Bass Strait, the outcrop of Dundas Group rocks is interrupted by two basement wedges. Each wedge rides on a high angle, possibly reverse, fault which has the western side upthrown.

The eastern-most fault has been named the Ulverstone

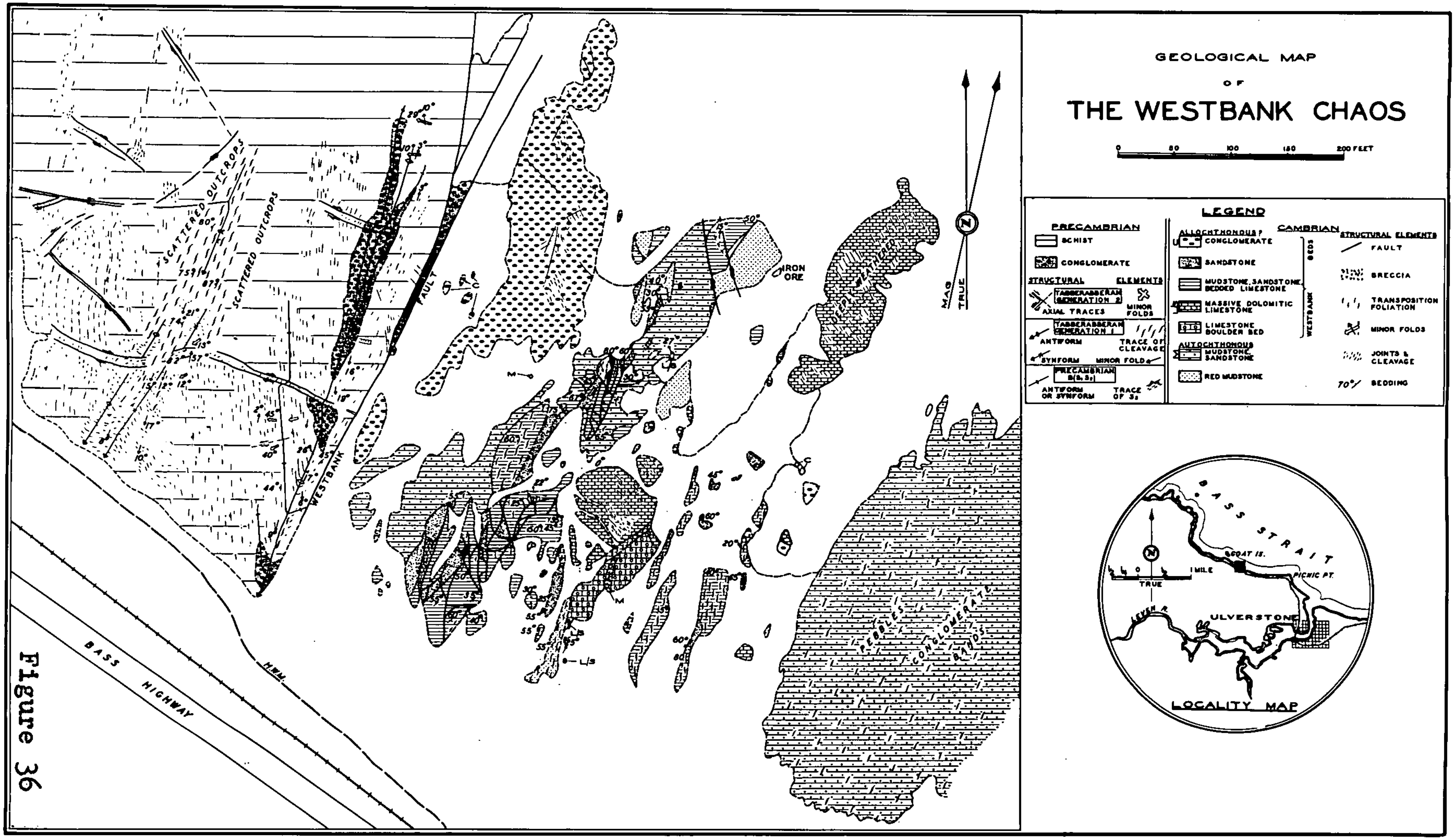
Fault. Where this crosses the Leven River, the fault wedge contains 1600 feet of unsheared Dundas Group which dips 45 degrees west towards the fault. On the shore of Bass Strait, less than fifty feet of strongly sheared Dundas Group mudstone is preserved in the angle between the fault and the unconformity.

The western fault has been named the Westbank Fault. At the Leven River the fault is entirely within Precambrian but on Bass Strait several hundred feet of Dundas Group rocks are preserved on the downthrown, eastern side of the fault. This outcrop of Cambrian is the Westbank Chaos. (figure 36).

Westbank Chaos: As previously indicated in discussion of the stratigraphy, the Chaos is probably a sheared megabreccia and contains allochthonous conglomerate, mudstone, sandstone, limestone and dolomite as large boulders in a matrix of autochthonous sandstone and mudstone. Portions of the chaos are strongly sheared, however, and many of the boulders have the appearance of tectonic inclusions.

The definitive features of chaos structure, after Noble (1941), are as follows.

1) The type chaos, the Amargosa Chaos of Death Valley, consists of a discordered mass of large and small blocks of irregular shape - a "cyclopean scale" breccia. At Westbank, blocks range from six inches to 300 feet in length.



GEOLOGICAL MAP
OF
THE WESTBANK CHAOS
0 50 100 150 200 FEET
LEGEND
PRECAMBRIAN
SCHIST
CONGLOMERATE
STRUCTURAL ELEMENTS
TABBERABBERAN GENERATION 2
AXIAL TRACES
MINOR FOLDS
TABBERABBERAN GENERATION 1
ANTIFORM
SYNFORM
TRACE OF CLEAVAGE
MINOR FOLD
PRECAMBRIAN
ANTIFORM OR SYNFORM
TRACE OF S_2
CAMBRIAN
ALLOCHTHONOUS ?
CONGLOMERATE
SANDSTONE
MUDSTONE, SANDSTONE, BEDDED LIMESTONE
MASSIVE DOLOMITIC LIMESTONE
LIMESTONE BOULDER BED
BEDS
WESTBANK
AUTOCHTHONOUS
MUDSTONE, SANDSTONE
RED MUDSTONE
STRUCTURAL ELEMENTS
FAULT
BRECCIA
TRANSPOSITION FOLIATION
MINOR FOLDS
JOINTS & CLEAVAGE
70° BEDDING
SCATTERED OUTCROPS
SCATTERED OUTCROPS
FAULT
WESTBANK
IRON ORE
MAG
TRUE
N
PEBBLES
CONGLOMERATE
BASS HIGHWAY
H.W.M.
BASS STRAIT
GOAT IS.
PICNIC PT.
ULVERSTONE
LEVEN R.
1 MILE
TRUE
LOCALITY MAP

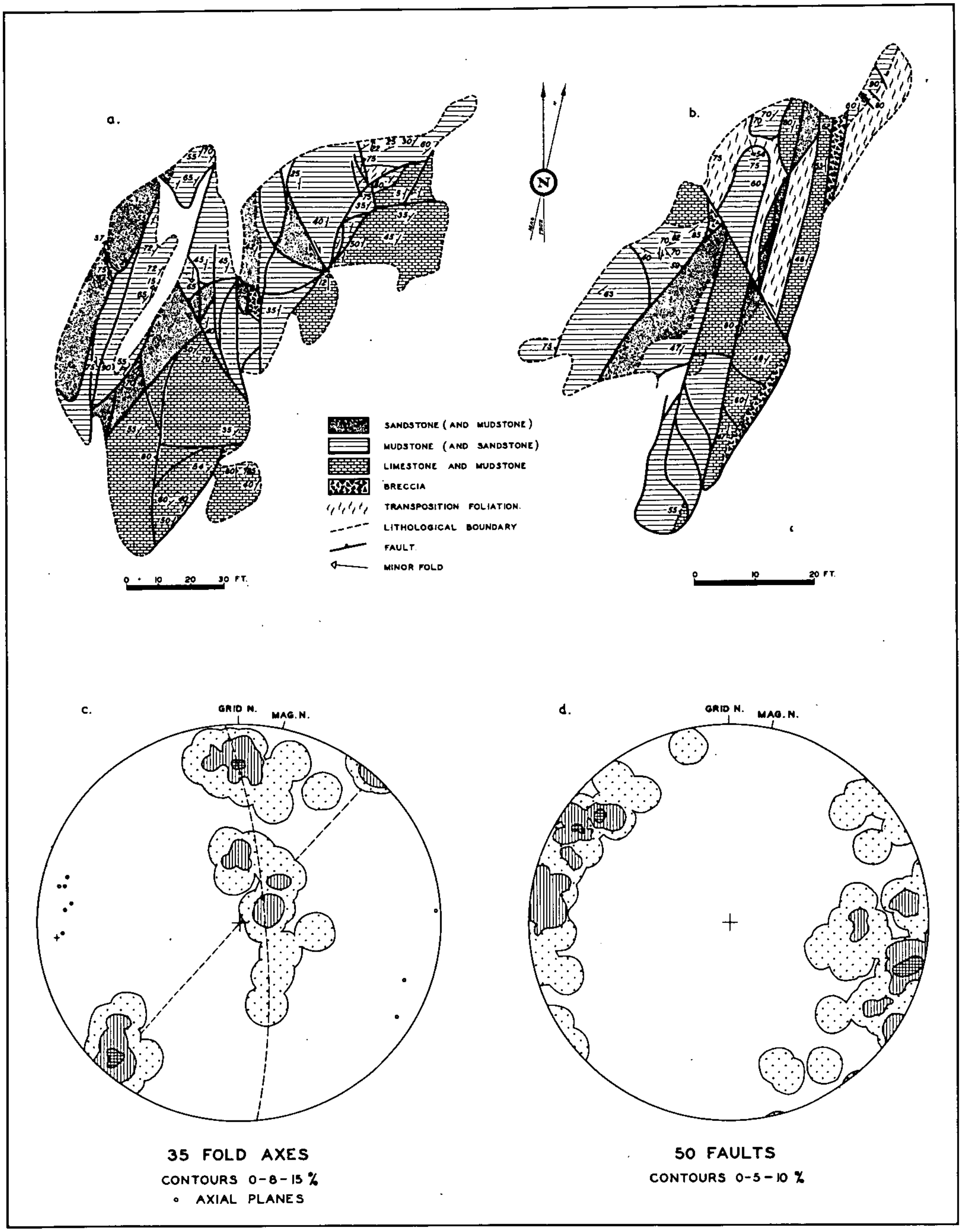
Figure 36

2) The blocks have lenticular or elongate shapes, with blunt or tapering ends, with bedding lying parallel to the flat surfaces of the blocks. At Westbank, small blocks (below three feet diameter) are elongate or ellipsoidal in shape, with the bedding contorted within the block in such a way that it is subparallel to the boundaries of the block at the outer margins. This is a structure typical of "rolled-up" tectonic inclusions. Some small blocks, and all the large ones, have bedding that is gently folded and truncated by the block boundary.

3) Each block, in both the Amargosa and Westbank Chaos Structures, is bounded by surfaces of movement. At Westbank, the movement surfaces are steep, curving faults or zones of strong shearing.

4) Each block of the Amargosa Chaos is minutely fractured throughout. In the Westbank Chaos, the fracturing takes the form of numerous faults and shear zones. Sketch maps of this internal structure of two large blocks are reproduced in figure 37a,b.

5) The arrangement of blocks is confused in detail, but ordered overall. Kupfer (1960) found in the Riggs Chaos that the ordering consisted of preservation of the normal stratigraphic order; that is, blocks of younger formations overlay blocks from older formations. He found,



The Westbank Chaos

a,b: Sketch maps of allochthonous slabs
c,d: Lambert projections of folds and faults

Figure 37

also, that the stratigraphic succession was "skeletonized", a stratigraphic section several thousands of feet thick being represented by blocks totalling only a few hundred feet thick. At Westbank, there is no evidence of the extent of "skeletonization" but a stratigraphic order is maintained, blocks of similar lithologies lying in zones trending north-east. The western zone is conglomerate, east of this is a zone of interbedded mudstone, sandstone and limestone, and there is an eastern zone of massive, calcareous dolomite.

Chaos structures are similar in appearance to megabreccias. The Westbank Chaos is identified as a "chaos" for two reasons.

First, boulders in a megabreccia are rarely internally faulted. Where internal deformation occurs, it is of a soft sedimentary type, usually "auto-brecciation" with pull-apart and breccia structures in an annealed groundmass. The boulders in the Westbank Chaos, on the other hand, are, if small, tightly folded, and if large, broken up by internal faulting (figure 37a,b).

Second, in a megabreccia the blocks and slabs are differentially rotated, but not on distinct movement surfaces. The blocks in the Westbank Chaos are bounded by movement surfaces.

There are, however, reasons for considering the Westbank Chaos to be a sheared megabreccia. First, there is a lithological contrast between the boulders and the clastically deposited matrix, as in a megabreccia. In a chaos, the matrix is entirely tectonically generated breccia or fault gouge and the chaos may be regarded as a large-scale fault breccia (Carey, 1962, p.99). The matrix is then composed of material similar to the blocks. This is not the case with the Westbank Chaos.

Second, the matrix of a "pure" chaos, that is, one generated entirely tectonically, is necessarily sheared throughout. The matrix of the Westbank Chaos is unsheared in a few places, particularly underlying the conglomerate belt.

Third, the lithological assemblage in the Westbank Chaos is the same as that in the Teatree Point Megabreccia near Penguin.

It may be noted that sediments of the Dundas Group outcrop in four localities on Bass Strait. The westernmost is the Beecraft Megabreccia at Penguin, which is sheared in only one narrow zone. A little further east is the Teatree Point Megabreccia, which is sheared in a number of narrow zones. The Westbank Chaos is extensively sheared. The Cambrian rocks on the footwall of the Ulverstone fault are strongly sheared and boulders of dolomite are tectonic inclusions derived from a bed near the base.

The Westbank Chaos is a sheared megabreccia, but it underlies the Westbank Fault. This makes it essentially different from the sheared megabreccias of the western United States. Whereas the United States examples were formed from debris at the nose of a flat thrust being pushed along or over-ridden by the thrust, the Westbank Chaos was formed by a high angle reverse, fault cross-cutting a pre-formed megabreccia. This implies that the megabreccia is substantially older than the principal movement on the fault. This is also implied in the identification of the Chaos as a sheared megabreccia - the megabreccia was formed, then sheared at a later date. This difference implies, also, that the United States and Westbank breccias have different modes of formation. This is the case, as the former are continental deposits, the latter marine, with a very different genesis.

Folding in the Westbank Chaos consists of gentle, open folds in the boulders which plunge at low angles to 360 and 220, together with closed, almost isoclinal folds in small boulders which plunge on steep axes (figure 37c). Axes of the steeply plunging folds tend to form a girdle dipping 70E355, parallel to the axial surfaces. The folds in the small boulders reflect the deformation of the matrix, and are of a very different style and orientation to the folds in the large boulders.

The girdle of fold axes is not due to refolding as no folds were observed in the cleavage. It would be expected that any crossfolds would be of a steep axial plunge secondary type (Ramsay, 1957), which would not rotate earlier fold axes into such a girdle, and which would refold the cleavage.

A second possibility is that the girdle results from synchronous crossfolding of the type described by Lambert (1959), which is characterised by a girdle of fold axes in the cleavage plane (Lambert, p.492). Lambert considers that Helford River folds formed as cross folded minor flexures, with the cleavage developed later.

The third possibility is that the girdle is due to superposition of shear folding on bedding which is highly variable in orientation. The fold axes in the girdle or figure 37c are then parallel to the intersection of bedding with the superimposed foliation. The beds had, therefore, an original dip up to ninety degrees, and could have had almost any strike. This possibility agrees with the deduction that this rock was originally a megabreccia, with disoriented boulders having bedding with a wide range of attitudes.

The foliation is not confined entirely to the matrix, but occurs within some of the large slabs, as indicated in figure 37b.

The bedded mudstones in the slabs have laminae averaging 0.02mm thick marked by alternations of a grey mosaic of quartz, chlorite and clay with black, carbonaceous mudstone. Where these are gently folded on axes plunging to 360, there is a weak cleavage marked by the alignment of secondary chlorite

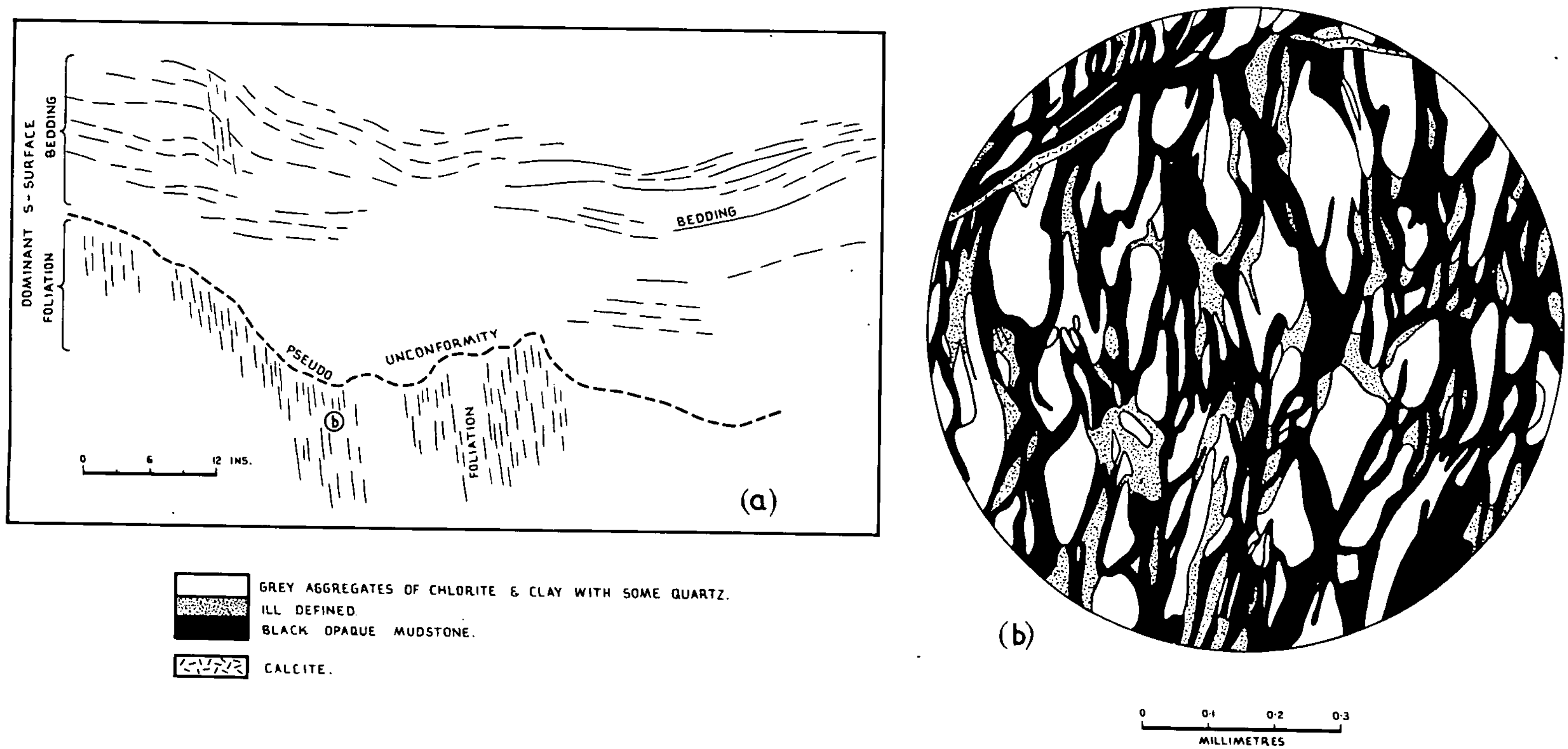


Figure 38

FOLIATION IN THE WESTBANK CHAOS

transverse to bedding.

In several places within the slab of figure 37a such weakly cleaved, gently folded mudstone overlies an area in which the foliation is strongly developed. The contact between the regions where the cleavage is weak, and where it is dominant, is an undulating boundary sub-parallel to bedding which resembles an unconformity. For this reason it is called a "pseudo-unconformity", as shown in figure 38. The foliation below the "pseudo-unconformity" consists of lenticular to sub-quadrate fragments of bedding (grey coloured aggregates of finegrained chlorite and clay, with occasional small quartz grains) with their long axes aligned vertically. The matrix is carbonaceous mudstone, derived from the more mobile layers. It is remarkable that this structure, requiring disruption and probably rotation of fragments of "rigid" layers, should terminate upwards at such a sharp boundary. This suggests the foliation was formed during flowage and the weakly cleaved beds were carried as a raft in the flowing zone. If this is the case, it suggests that the folding occurred during squeezing of material entrapped in the Westbank Fault zone.

The observed faults are plotted in figure 37d. The measurements indicate little more than that the faults tend to be oriented parallel to the Westbank Fault. The fault style is unusual. Pairs of faults are frequently linked by sigmoidal shears, and sometimes the sigmoidal areas defined by the shears contain within them another set of sigmoidal shears (figure 37a). Some of the faults are brecciated but the majority are zones of concentrated shear.

The sigmoidal shears intersect with a small triangle of sheared rock at their junction, and with no discernible offsetting. It is possible that the lack of offsetting means that the fault movements were parallel to their lines of intersection, but it is more likely that the phenomenon is of genetic significance. It has been observed in some exposures of the matrix that the sigmoidal shears form intersecting, opposed sets with the dihedral angle between them bisected by the foliation. The style implies that the sigmoidal shears were formed essentially simultaneously, and at much the same time as the foliation. The phenomena can be explained by supposing a laminar flow along the foliation in less competent lithologies, formation of the sigmoidal shears in either more competent lithologies, or at higher strain rates. The sigmoidal shears form, in any place, strain-controlled conjugate sets (cf the Schmidt "wedge" of Fairbairn, 1949, pp.205-207; and the slip lines of plastic flow of Jaeger, 1962, pp.143-149). Presumably the shears are generated in plastic extrusion flow of rocks squeezed in the fault zone.

An east-west axis of compression is indicated by a pair of shear joints found in one slab which are vertical and strike at 230 and 300, with dextral and sinistral strike-slip respectively, implying an axis of maximum principal stress directed to 265.

The orientations of the folds and axial-surface foliation agree with Tabberabberan structures of the area.

<u>Cateena Point Slump Zone</u>: On the south bank of the Leven River at Cateena Point mudstones of the Cateena Subgroup are well exposed in the inter-tidal zone. A group of folds low in the succession are gravitational slump folds formed contemporaneously with deposition. A number of folds higher in the section are tectonic. This outcrop forms the lower plate of the Ulverstone Fault.

Figure 39 is a general map of the slump zone at Cateena Point. The folds are confined to a layer about 100 feet thick. The beds in the slump zone have nearly vertical dips, the beds west of the slump zone have the general regional dip averaging 50W040. As has been discussed, the slump zone is confined to a "macro-graded" succession of greywacke sandstone and conglomerate.

The "Undisturbed" beds overlying the slump zone are mudstones containing fine grained sandstones and siltstones without coarse greywacke. Bands of tough siltstone are boudinaged and some siltstones have minor sedimentary dykes.

The slump zone has three principal structural types, slide areas, contorted zones, and brecciated zones.

In the slide areas the bedding is uniformly oriented. All

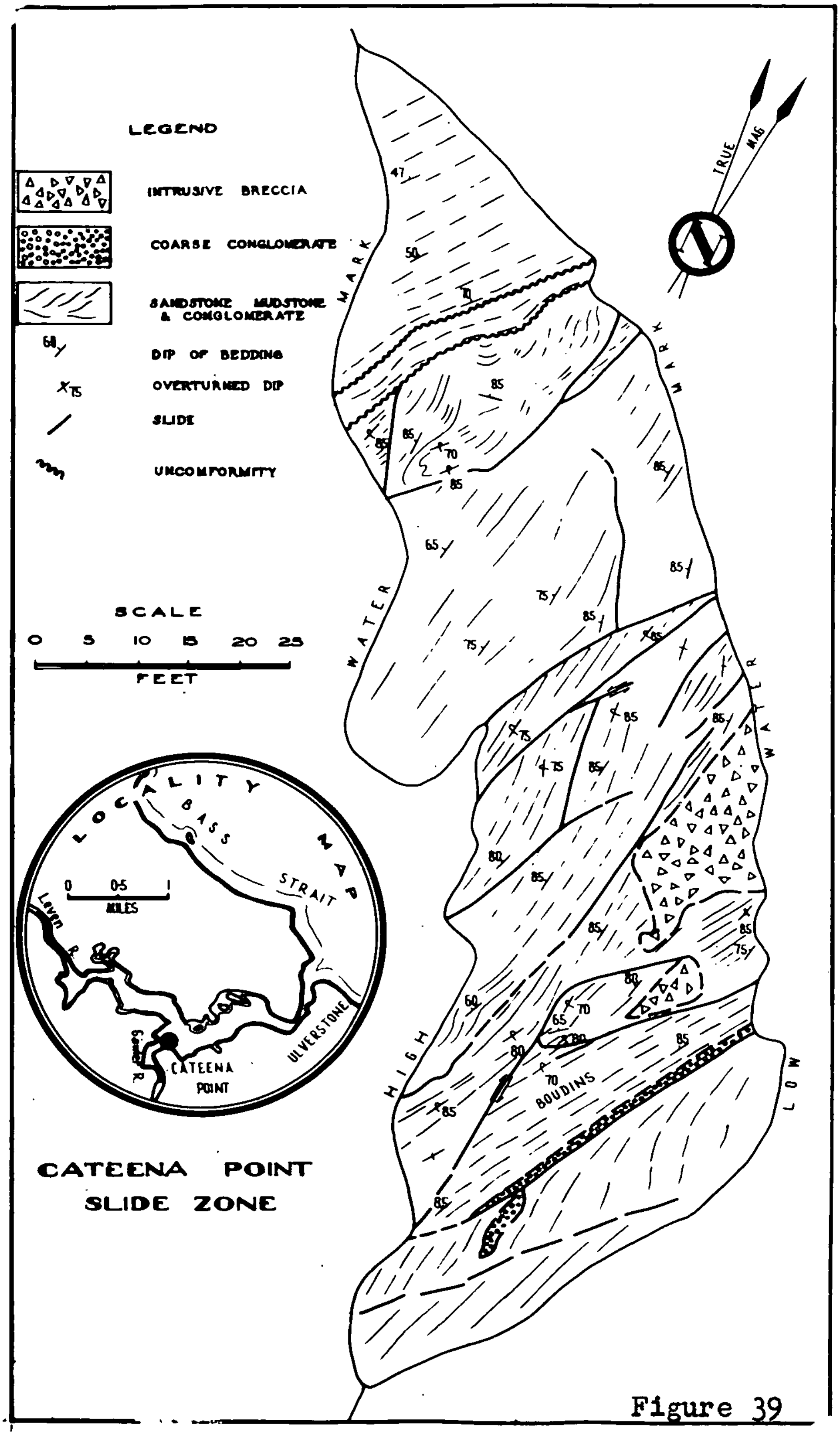

LEGEND
INTRUSIVE BRECCIA
COARSE CONGLOMERATE
SANDSTONE MUDSTONE & CONGLOMERATE
DIP OF BEDDING
OVERTURNED DIP
SLIDE
UNCOMFORMITY
SCALE
0 5 10 15 20 25
FEET
LOCALITY MAP
BASS STRAIT
0 0·5 1
MILES
Leven R.
ULVERSTONE
CATEENA POINT
TRUE
MAG
HIGH WATER MARK
LOW WATER MARK
BOUDINS
CATEENA POINT
SLIDE ZONE

Figure 39

the beds face the same way, from the evidence of graded bedding, so the overturned dips are due to gentle folds on inclined axes. In general, the bedding is gently curved in the slide area and truncated abruptly by the slide. The truncation is usually at the top (west side) of the slide area, the slide at the lower surface being conformable with bedding. The slides are sedimentary structures as a number of them show major, large-scale loadcasting of the slide surface, with flame structures up to twelve inches high.

In the contorted zones the bedding is frequently flat-lying, with some well-defined folds. Although some of the folds are closed, no axial jointing or cleavage is developed. In the strongly congested hinges accommodation was by brecciation. Some beds in these zones show a reversed grading. This is not thought to be due to multiple or composite grading as most of the beds in the macrograded succession are simply graded. One of the beds with reversed grading was excavated and found to be prolapsed, that is, folded back on itself. One well formed fold (plate 18) has the form of a folded sac, with the sandstones of the rim prolapsed. The sac is the nose of a recumbent fold.

The brecciated zones contain a chaotic jumble of large pieces of mudstone. A very coarse breccia (much coarser than any of the bedded conglomerates) is injected as a dyke transverse to bedding (plate 18a). The dyke terminates downward on a sedimentary slide (with large flame structures)

Plate 18

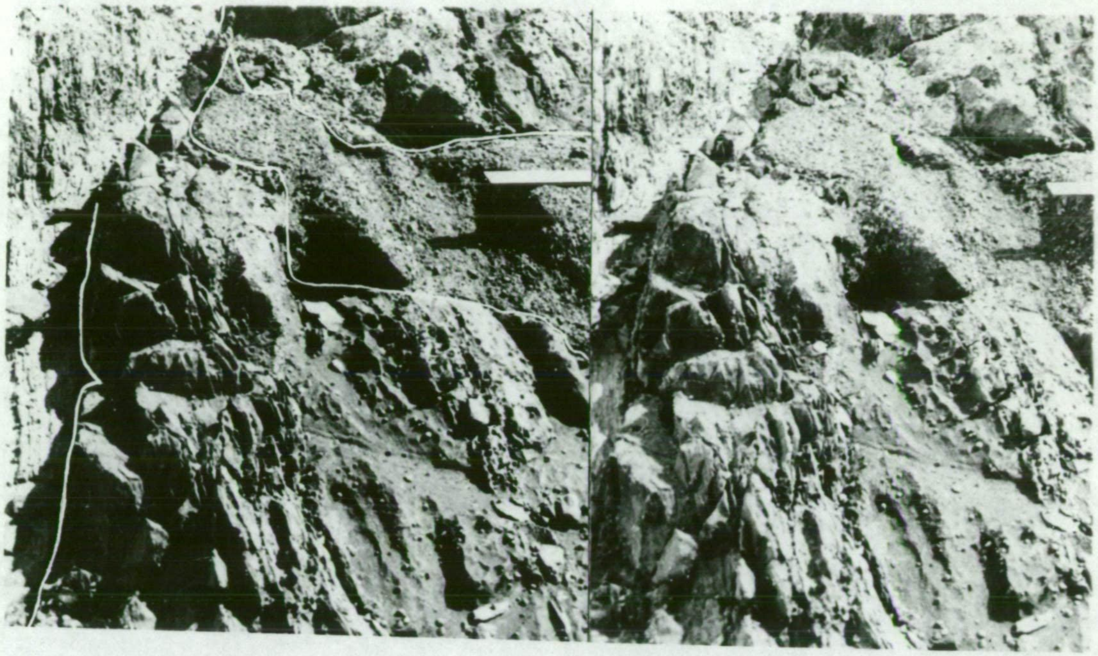
Cateena Point slide zone.

a: Sedimentary slide, with a large flame structure in the foreground, offsetting a clastic dyke of "autobreccia".

Stereoscopic pair. Scale: six inches long.

b: Nose of an isoclinal fold.

Hammer handle is one foot long.



a

b

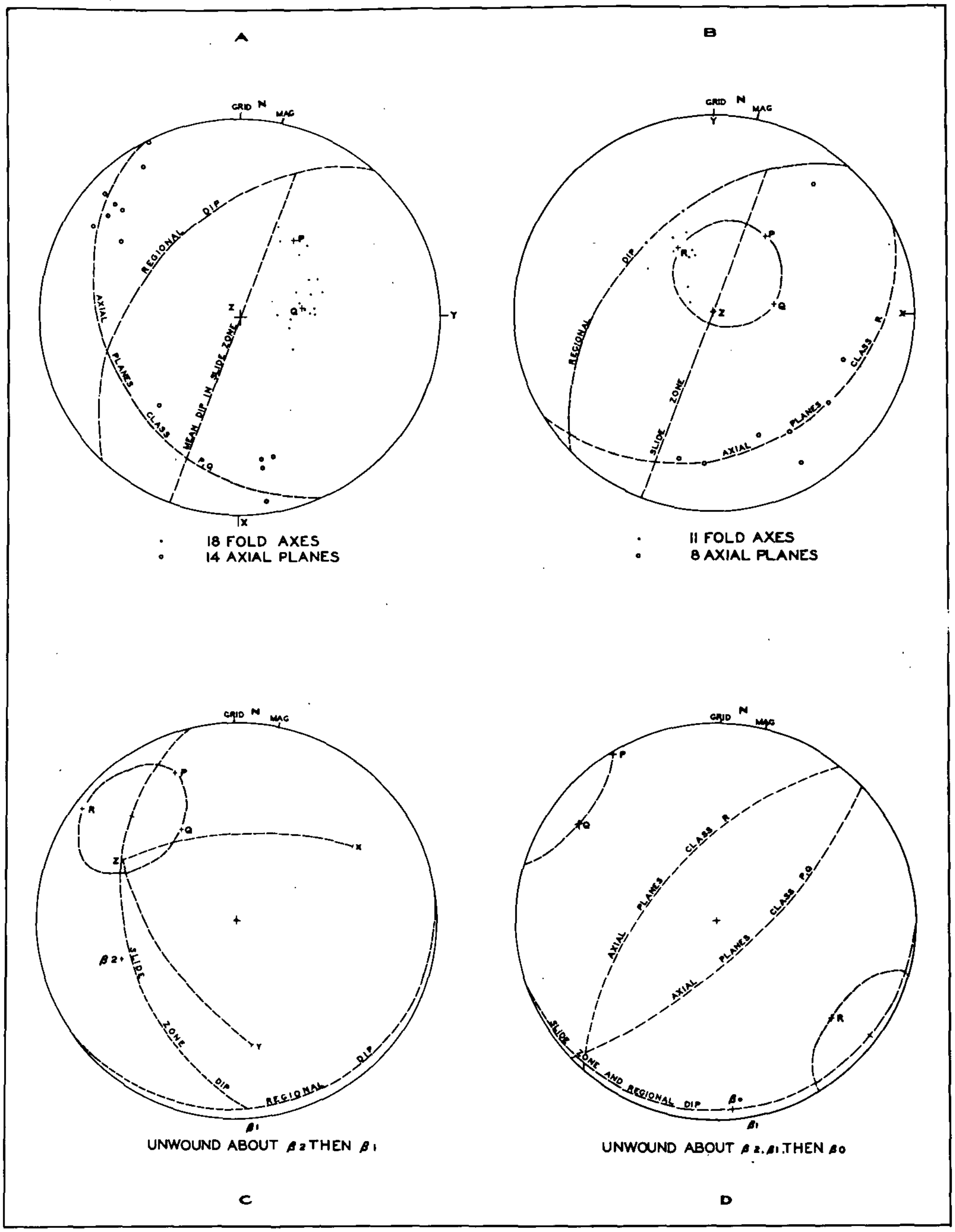
so that the "autobrecciation" that produced the dyke material either preceded, or was contemporaneous with, sedimentary sliding.

Rich (1950) distinguishes between intrastratal contortions and "larger crumplings", or interstratal contortions. The interstratal folds occur in narrow belts which have sharp margins. The folds in the belt usually plunge at an angle to the margins. Bedding is confused and obliterated in parts. Folding occurs without fracturing, indicating sediments only weakly consolidated.

Fairbridge (1947) has described similar folds and notes that the fold zones are bounded against undisturbed sediment below by a slide surface, and have their tops bevelled by erosion. He notes complex folding without cleavage, and that the fold axes "ignore" the local tectonics. Kiersch (1950) has noted folds with a basal slide, overlain unconformably by undisturbed bedding.

Brindley and Gill (1958) divide the slump zones into sheets or channels, and note that the tops are planed off by erosion. The sediments in the slump zones has been broken into rafts, or "balled up" with sandstone balls floating in a matrix of mudstone. Sand volcanoes on the slumps (Gill and Kuenen, 1958) indicate internal breakdown of the sandstones.

The Gawler slump zone is representative of a widely distributed phenomenon. It has the essential characters of



CATEENA POINT SLIDE ZONE

Figure 40

interstratal folds, which are an unconformity at the top, cognate sedimentary slides, folds without cleavage, and evidence of some mobilisation of the sediment in the autobreccia and sedimentary dykes.

In the contorted zones the folds are of two kinds, isoclinal and open. The axes of the isoclinal folds plot near Q of figure 40a. The open folds plot at P, with some axes near Q. The two styles are contemporaneous, as their axes have the same general orientation, and as the open folds refold one limb of the closed fold of plate 18b, but not both limbs. That is, they do not refold the axial surface of the closed fold.

In both contorted and slide zones are a number of asymmetrical, open folds, facing south. Their axes plot near R of figure 40b. The axial surfaces strike generally south-west, which is an orientation similar to the tectonic folds higher in the succession. The difference in plunge could be due simply to their being superimposed on beds with a steeper dip than the regional dip. One of these folds has an axial surface thrust.

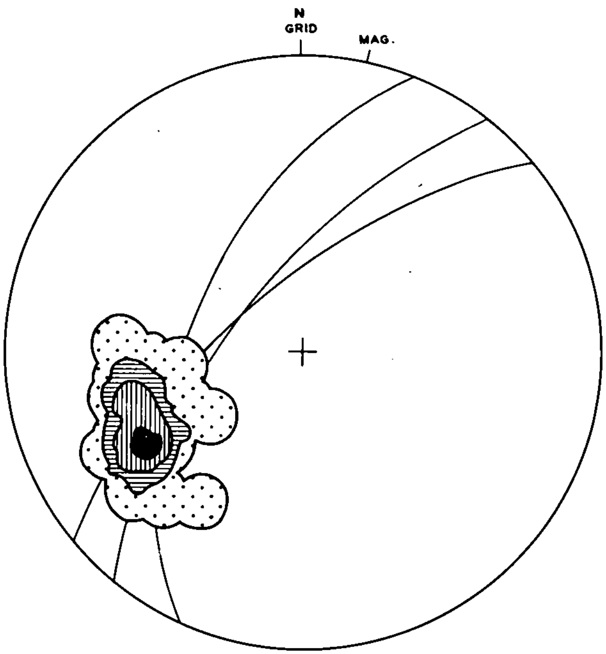
The beds at Cateena Point are tectonically doubly folded, about axes B2, and B1 of figure 40c. In this figure, the fold axes in the slide zone have been unwound about B2 and B1. This unwinding leaves a remnant regional dip of 6SE080, which is plausible. The mean dip of the slide zone is still large.

As this dip was acquired during sedimentation, the axis of sedimentary rotation was BO of figure 40d, at the intersection of the slide zone and regional dips. Unwinding about BO gives figure 40d.

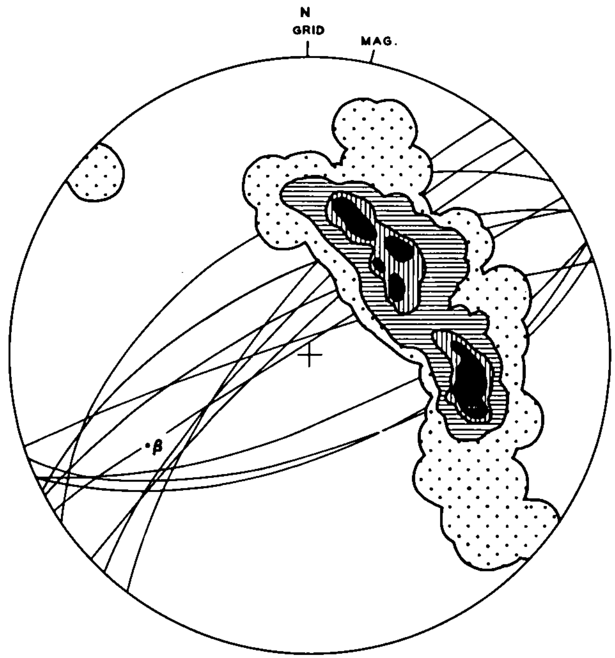
To facilitate the unwinding, the axes of folds in the slide zones have been represented by the three points P,Q, and R, which lie on a small circle. If the small circle has any significance, it is merely that folds axes form a conical pencil with axis in the bedding, a distribution to be expected in sac-form folds resting on a slide.

The folds type P and Q, the assuredly sedimentary folds, have restored axes striking 320, transverse to 230. As shown by the unconformity at the top of the slide zone and confirmed by details of style, the folds were formed at the time of sedimentation, that is, during the Middle Cambrian. Similar folds are known from the top of the succession at Cateena Point in another macrograded unit, and from the Teatree Point Megabreccia.

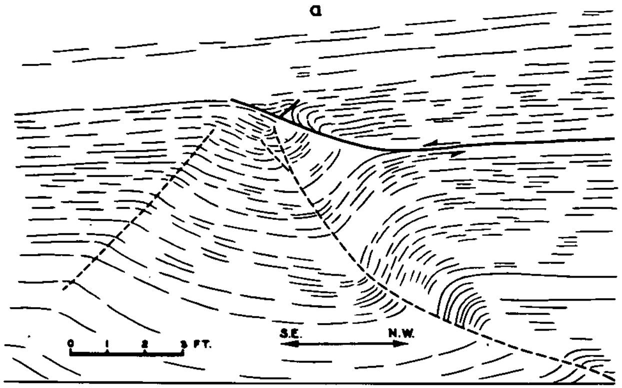
Cateena Point Tectonic Folds: In the "undisturbed" beds overlying the Cateena Point slide zone are a number of tectonic folds. These are characterised by a very regular axial direction, uniformly oriented and sometimes contraposed axial surfaces, and bedding plane thrusts. The accommodation to folding was entirely by bending, thrusting, or by means of axial "knick planes". The regularity of the folds is shown



a



b



c

a. 38 FOLD AXES: CONTOURS 0 – 13 – 26 – 39 % MAXIMUM 45 %
3 TRACES OF THRUST PLANES.

b. 128 BEDDING POLES: CONTOURS 0 – 4·5 – 9 – 11 % MAXIMUM 14·5 %
11 TRACES OF KNICK PLANES.

c. AXIAL PROFILE OF A FOLD.

FOLDS IN CATEENA MUDSTONE WEST OF CATEENA PT.

Figure 41

by figure 41b, where bedding poles from a number of folds are plotted on the one diagram.

As shown by the profile of figure 41c, the folds have a conjugate profile (Johnson, 1956) with only one fold pair developed. Sometimes the lower pair is developed, as in the illustration, sometimes only the upper. The most frequently observed folds were south-facing folds of the upper pair. The folds thus die out, above and below, onto bedding plane thrusts. The thrusts are therefore compound structures, as the slip is not the same at all points on the thrust surface.

There is no direct evidence of the age of this folding. It is probably Tabberabberan, as the folds are steep axial plunge secondary folds of similar profile and orientation to the third generation of Tabberabberan folding at Eugenana.

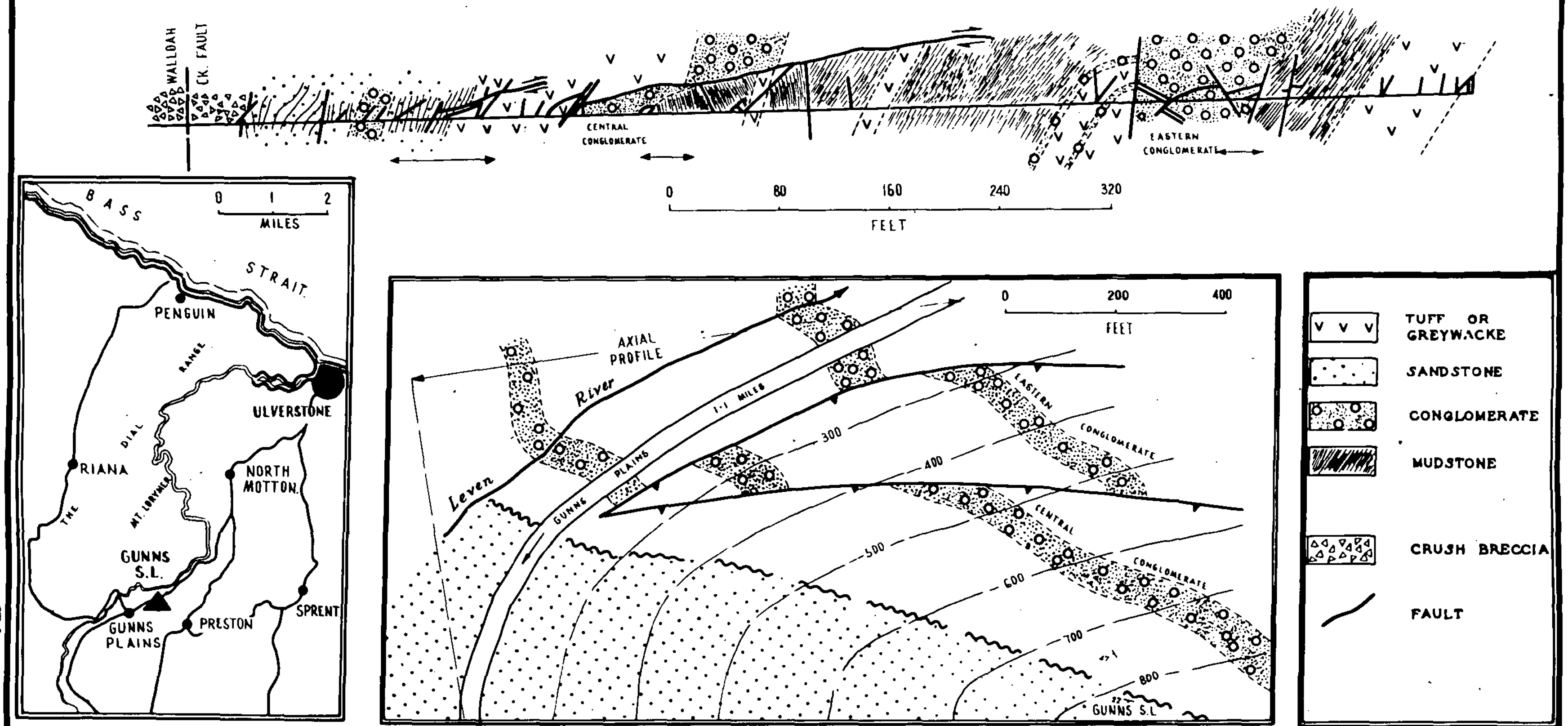
Sugarloaf Gorge

Three conglomerates outcrop in the Sugarloaf Gorge of the Leven River at Gunns Plains - the western, central and eastern conglomerates of figure 42. The western conglomerate consists mainly of flaggy sandstones and is correlated on lithological grounds with the Moina Sandstone.

Cambrian fossils have been found in the mudstones between the eastern and central conglomerates.

The central and eastern conglomerates may be either:

1) Cambrian conglomerates, interbedded with the Cambrian mudstones and tuffs, or



ROAD SECTION GUNNS SUGARLOAF

Figure 42

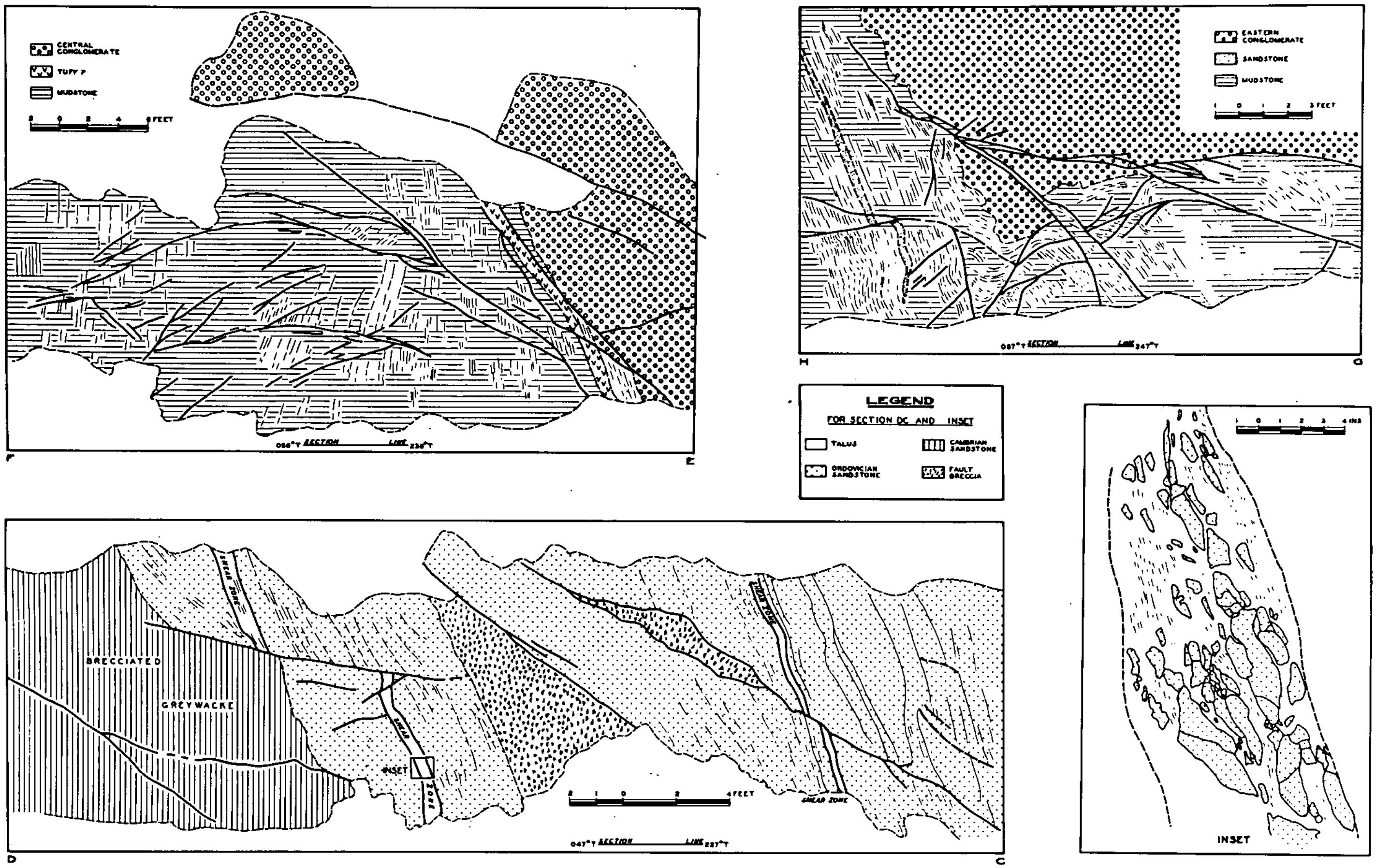
2) basal conglomerates of the Moina formation repeated by faulting in an imbricate thrust zone.

The first alternative was adopted by Banks (1956, p.184). At that time it appeared that the western boundary of the eastern conglomerate was gradational with Cambrian sandstone and mudstone and the conglomerate contained a band of mudstone dipping thirty-four degrees east. However as a result of roadworks since 1956, it can be shown that the western boundary of the eastern conglomerate is a vertical fault making a very low angle with the road cutting, so that the fault trace is very irregular on the cutting. Conglomeratic patches in the sandstone are, in effect, "windows" through the fault surface. The band of mudstone in the conglomerate is a fault sliver containing lenticular inclusions of conglomerate and is not a bed.

At the top of Gunns Sugarloaf the central conglomerate is truncated by the base of the western. This may be either an unconformity or a fault at the base of the western conglomerate.

The eastern boundaries of the central and western conglomerates appear to be unconformities, but there is strong differential movement at these contacts (figure 43) and the existence of unconformities cannot be proven.

The general structure could be either an imbricate fault zone or a Cambrian succession containing interbedded



DETAILS OF ROAD SECTION-GUNNS SUGARLOAF

Figure 43

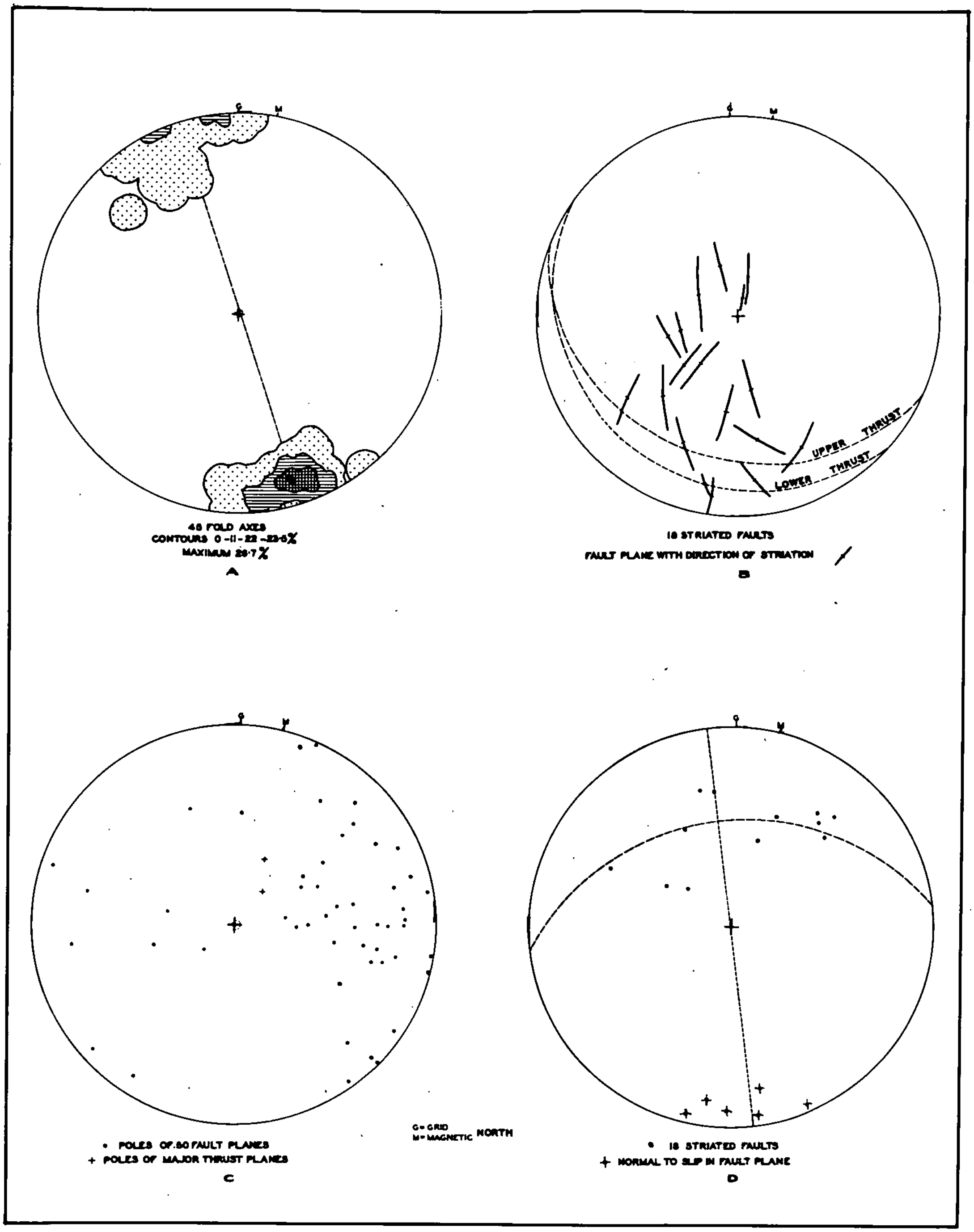
conglomerates which is overlain unconformably by the Moina formation.

A number of minor folds within the mudstone are open, concentric, with axial surfaces vertical except where rotated by later faults. The mean plunge is 10-164. (figure 44d). One minor fold in the Moina Sandstone has this plunge. This orientation is close to that of folds in the Gordon Limestone half a mile to the northwest. The folds are therefore of Tabberabberan age.

The road section contains numerous faults. Three fault types are recognised.

The first fault type consists of breakthrusts, sub-parallel to bedding, which curve over the crests of minor folds in two opposed senses. The direction in the fault plane which is normal to the slip (the "b-axis" of slip) is parallel to the fold axes (figure 44d). The fault planes form a sheaf co-axial with the fold axes. The faults were thus developed pene-contemporaneously with folding.

A second type consists of high angle faults. These are best developed in the Moina Sandstone, which is not parallel-bedded, but is a stack of lenses emplaced by faults sub-parallel to bedding. Included with this type are shear zones, which have wide fault zones containing lenticular tectonic inclusions of wall rock (figure 43). The oblique-slip faults



The Sugarloaf Gorge

Lambert projections of folds and faults

Figure 44

plotted in figure 44b are assigned to this class. The distribution of striational plunges for the secondary type of faulting (figure 44b) suggests the wrench-normal association of Williams (1958). This possibility was tested using Williams' criteria, for the faults as mapped, and for the faults rotated to be co-axial about the lines 0-170 and 0-240, but in no case do his criteria fit all the faults. A plot of "normal planes" was made, that is, of planes containing the pole of the fault and the striation direction (compare Clark and McIntyre, 1951b), but the intersections of the normal planes were random.

It is likely that the major, Walloa Creek fault belongs to this fault class. The movement on the Walloa Creek Fault is dextral with a normal component of dip-slip. The striational plunges on faults of this class match, approximately, Williams figure 2, for the wrench-normal association. It is probable, therefore, that these are wrench-normal faults.

The divergence of the fault planes from the orientations predicted by Williams means that the faults are not surfaces developed in an homogeneous body, but that the faults have inherited earlier movement surfaces. This being so, the analysis of Bott (1959) is applicable. Following Bott, the southwest dipping faults are dextral wrench or gravity, while the southeast dipping faults are sinistral wrench or gravity.

Considering the whole fault class, if B is parallel to the fold axes, and C is vertical, then the regime (after Harland and Bayly, 1958) lies in the secondary fields wrench, axial, or gravity.

Forming a third fault class are the two major thrust faults. This class is the youngest, the faults off-setting all earlier structures.

The succession in the Sugarloaf Gorge is therefore:

1) Folding, with penecontemporaneous breakthrusting,
2) Oblique slip faulting,
3) Thrusting, with flat-lying crossfaults.

Mt.Lorymer

Mt.Lorymer is composed of a thick lens of Barrington Chert, at least 2800 feet thick. The general form is a doubly plunging anticline elongated in a northeast-southwest direction. The direction of elongation is the direction of a number of small, open flexural folds exposed on the crest of the range. The form surfaces show the mountain is cross-folded with other set of folds trending north-west. Figure 45 shows the general structure.

In appendix 3 a nomogram is reproduced, designed for unwinding superposed flexural folding. The amount of rotation of bedding in each fold phase can be deduced from this nomogram. The application to Mt.Lorymer is shown in figure 46. From this figure, the position of the superposed axial

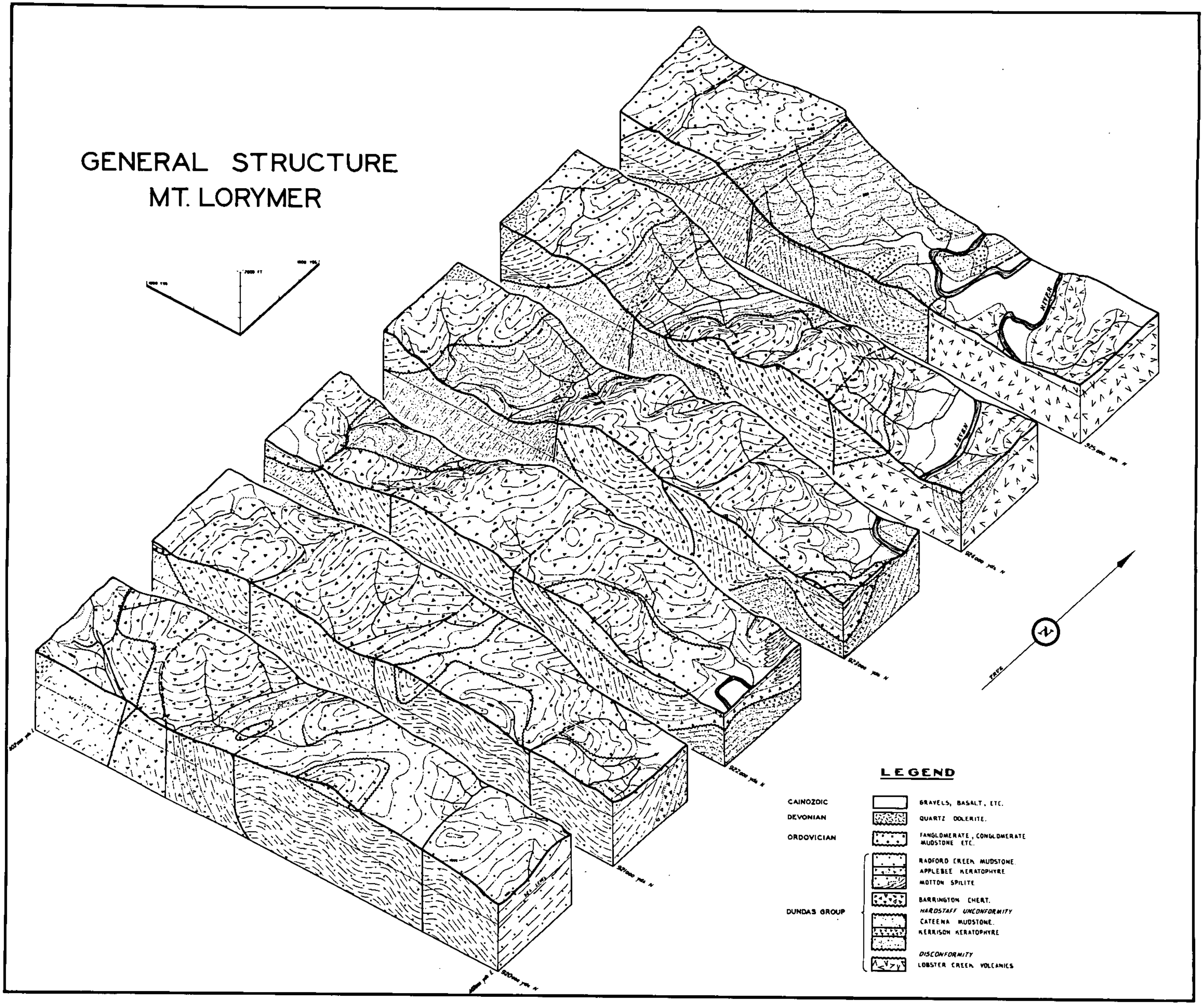

GENERAL STRUCTURE
MT. LORYMER
LEVEN
RIVER
LEGEND
CAINOZOIC
GRAVELS, BASALT, ETC.
DEVONIAN
QUARTZ DOLERITE.
ORDOVICIAN
FANGLOMERATE, CONGLOMERATE MUDSTONE ETC.
DUNDAS GROUP
RADFORD CREEK MUDSTONE.
APPLEBEE KERATOPHYRE
MOTTON SPILITE
BARRINGTON CHERT.
HARDSTAFF UNCONFORMITY
CATEENA MUDSTONE.
KERRISON KERATOPHYRE
DISCONFORMITY
LOBSTER CREEK VOLCANICS

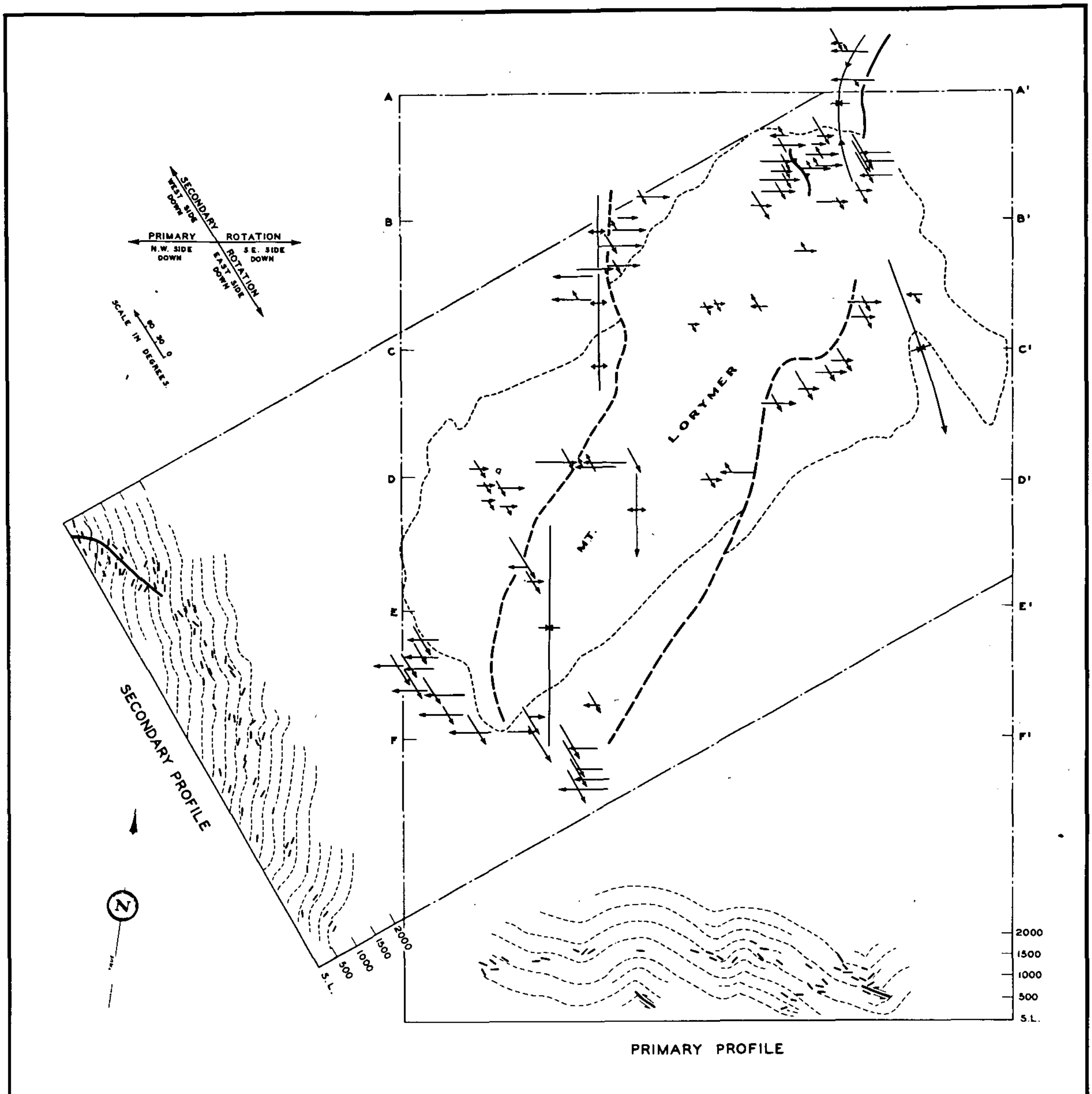
Figure 45

lines can be deduced.

It is assumed from the evidence of adjacent regions, that folds on northwest trends are older than folds on southwest trends. Then the northwest profile was established in horizontal, or near-horizontal beds, and has been refolded. The southwest profile was established on a folded terrain and should therefore undulate across the earlier folds.

Using the values of primary and secondary rotation in the same manner as dips, composite vertical profiles, in the sense of Wegmann (1929) were constructed for each fold direction, yielding "analytical profiles" of figure 46. The "secondary" profile shows only minor peturbations on a regional dip so that in correcting the profile of the northwest folds it was necessary only to allow for this regional dip.

Using the "analytical profile" as a controlling guide, a "composite vertical" profile of the north-west trending folds was constructed, as in figure 47. There is an unavoidable vertical exaggeration in this profile. It does not represent an actual profile in any one place, but is rather the sum of a series of surface profiles. Each surface profile would probably change in depth, (note discussion of this problem by Wilson, p.18, and McIntyre, p.20, of McIntyre, 1951). In the present instance, there will be a dramatic change of profile on crossing the boundaries of the very thick chert lens.



ANALYTICAL PROFILES – MT. LORYMER

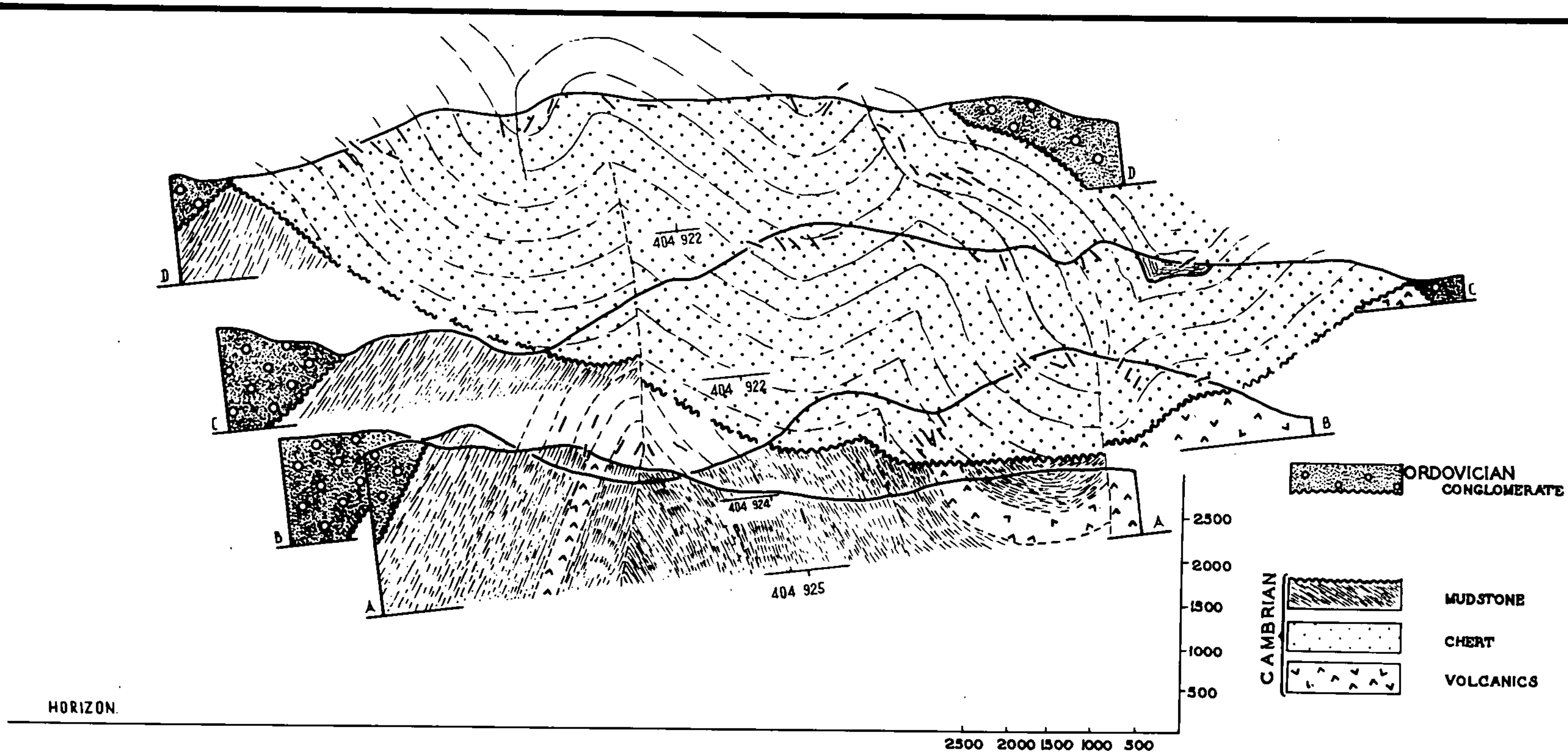
Figure 46

Despite the indirect way in which the profile of figure 47 was constructed, it agrees with the observed geology. This profile shows differing styles of folding of the chert and the underlying mudstone. The mudstone is folded into tight, almost carinate folds, with a slaty cleavage developed in the core of the anticline. The chert is folded into rounded, open folds associated with bedding plane thrusts. As closely as it is possible to determine, the folds in each lithology correspond in position and orientation. The fold style, therefore, is competent-incompetent, as for example, in Fairbairn (1949, fig.12-2a, p.160). At Mt.Lorymer there does not appear to have been translation along the Hardstaff Unconformity at the base of the chert.

Lobster Creek

In the centre of the Dial Range Trough near the Leven River, there is strong cross-folding defined by the form surfaces.

Outcrops are poor and there is only fragmentary evidence of the constituent axial trends. In the Library Syncline the chert contains minor folds plunging southwest and northwest, but there is no positive evidence of the relative ages of these folds. The north-west trending folds contain a rotational joint boudinage plunging parallel to the axes of minor folds south of Hays Creek. The folds often have a coarse strain-slip cleavage, or "bc" jointing, which at



COMPOSITE VERTICAL PROFILE OF MT LORYMER

Figure 47

Myrtle Creek plunges nearly north, and is refolded on axes plunging northwest.

At the northern end of Mt.Lorymer, the synclinal troughs of north-west trending folds, defined by outcrops of Motton Spilite, are refolded around the nose of the perianticlinal structure in a structural pattern resembling the refolded Cuenabres Syncline of de Sitter (1960, p.192). This may not be refolding to the extent implied by de Sitter but may be a migration of the trough line of the syncline due to superposed plunging folds.

South and east of Mt.Montgomery the Lobster Creek Anticline has a crestal trace swinging through nearly ninety degrees. The swing is due to cross-folding. Allowing for the strongly transgressive base of the Barrington Chert in this vicinity, the profile of the anticline is uniform for much of its length. The Library Syncline is refolded in a sympathetic manner.

The form pattern of the Lobster Creek anticline indicates that either, the anticline had an axial surface dipping gently west which was refolded on an crossfold trending west, or that the axial surface is upright and refolded on an axis plunging very steeply west. The mapping shows the anticline is an upright open fold so the crossfold axes must plunge steeply west.

Scattered minor folds and slaty cleavage agree with the large-scale mapping, indicating a first generation of folding on north-west axes, which has been refolded. The crossfolds trend south-west at Mt.Lorymer and Cateena Point, east-west near Mt.Montgomery, and northwest at Myrtle Creek. The crossfolding has a "polyclinal" style.

<u>Iron Cliffs</u>

The geology of the Iron Cliffs Mine, Penguin, at the western boundary of the Dial Range Trough, has been described by Burns (1961b).

The Rocky Cape Group, and Cambrian mudstones which unconformably overly it, were folded together on axes trending to 212.

Limonite ores were then emplaced, as fissure fillings and replacements controlled by structures generated in the folding. The ore was probably formed by hydration of a Precambrian bedded haematite. The limonite emplacement was post-Cambrian, as it replaces Cambrian conglomerate in places; but pre-Ordovician, as detrital limonite and haematite are found in the Duncan Conglomerate.

The ore is offset by steeply dipping dextral slip faults which strike near 105. Other post-ore structures include a single minor fold, refolding the laminated iron ore, of asymmetric profile facing north, a steep axial plunge, axial plane striking southeast and an axis near 70-105. The folds pre-dating the limonite emplacement have rapid variations of plunge ascribed to the second folding.

Penguin

The Beecraft Megabreccia unconformably overlies quartzite of the Rocky Cape Group immediately east of Penguin. The beds in the megabreccia dip west, towards the unconformity, and are in fact truncated by the surface of the unconformity. The beds were deposited against a vertical face in the quartzite.

The surface of the unconformity has been polished by slippage. Grooves and striae on the surface plunge between 22-086 and 26-118, with a mean near 26-100. The slippage is due to sedimentary sliding, differential compaction, or differential deformation bounded by the surface. As a large fold of several hundred feet wavelength plunges towards the surface and is abruptly terminated at it, most of the slippage probably reflects movement during deformation.

Beta for the fold is near 25-210, the fold having an orientation and profile closely analogous with the tectonic folds at Cateena Point.

The Beecraft Megabreccia, the Teatree Point Megabreccia, and the Motton Spilite contain large flat thrusts. The thrust surfaces are exposed at intervals along the inter-tidal platform, marked by thick sheets of chloritic mylonite. There is possibly only one single thrust, undulating along the platform at an altitude close to sea level.

In each exposure, there is a major thrust plane, with strike-slip movement, dipping at low angles. Observed orientations are 1) 45E202, with striae pitching 80N, 2) 30E192, with striae pitching 55N, 3) 23W177, with striae pitching 80N. In each place the major fault has second order shears, oriented 1) 30S112, with striae pitching 5W, 2) 35S117, with striae pitching 35W.

Eleven observed faults and subsidiaries have an intersection close to 20-160. The faults appear to be a system related to the Eugenanan folding.

CHAPTER 8

STRUCTURES IN THE ROCKY CAPE GROUP

CHAPTER 8

Structures in the Rocky Cape Group

Introduction

The Rocky Cape Group constitutes the basement on the western side of the Dial Range. On the eastern side of the Dial Range Trough, Rocky Cape Group outcrops in a narrow belt bounded by Dundas Group on the west and by Ulverstone Metamorphics on the east. (Figure 3).

The structure has been examined at Sulphur Creek, where four phases of folding are recognised. The first and second phases are pre-Ordovician; the second and third phases are correlated with the Tabberabberan.

Structures of the two pre-Ordovician phases occur at Blythe Heads and pre-date the Cooee Dolerite which is dated at 700 million years B.P.

The Rocky Cape Group at Goat Island has a structural history similar to that at Sulphur Creek except that the Tabberabberan structures are of large amplitude and are not merely perturbations as at Sulphur Creek.

The second phase of Precambrian folding resulted in a schuppen structure which rests on a large basal thrust, the Singleton Thrust, which outcrops at Goat Island.

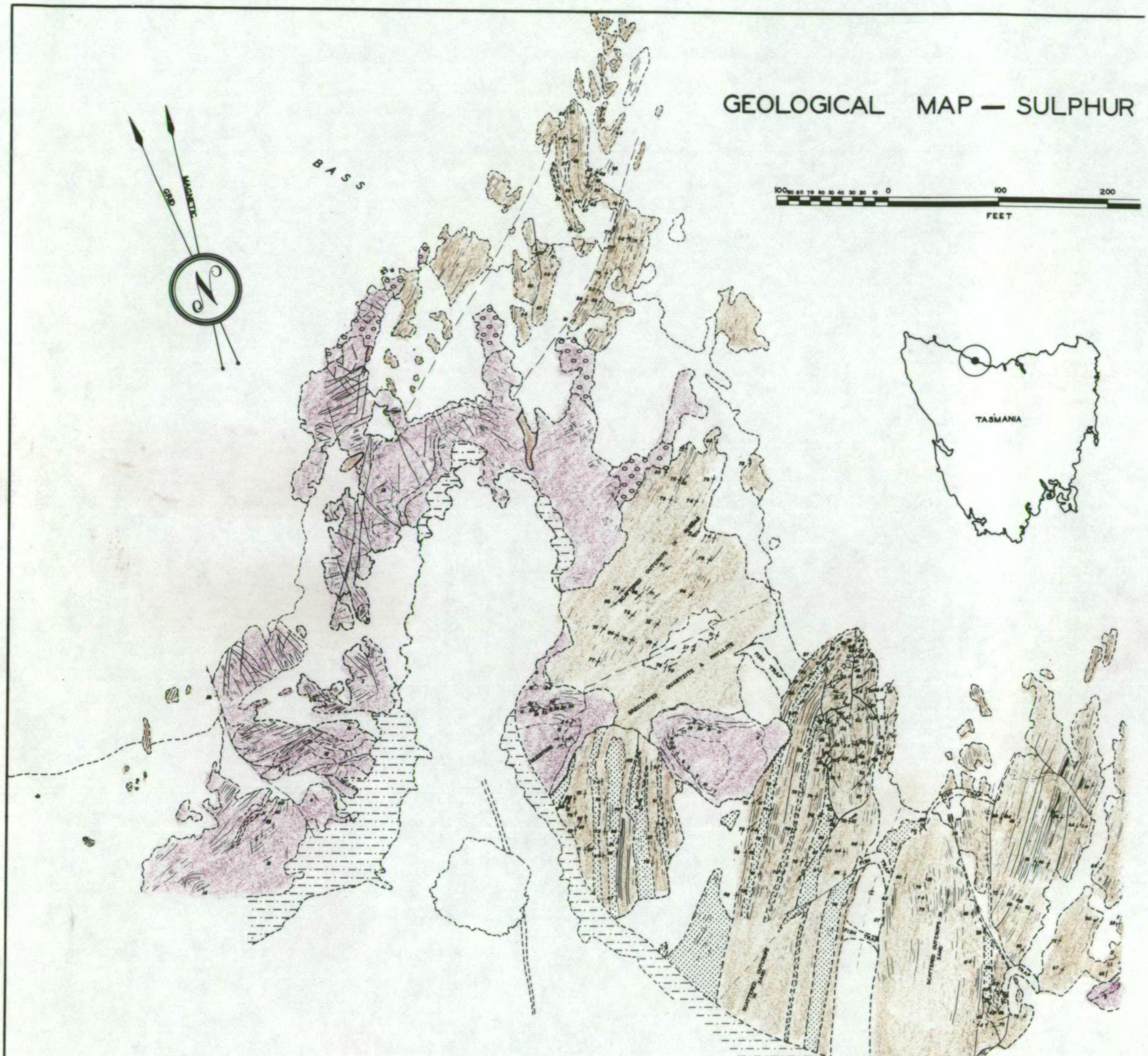
At the Iron Cliffs and at Penguin, there was disharmony between the Dundas Group and the Rocky Cape Group, that is, the unconformity between the two groups was a decollement.

<u>Iron Cliffs</u>

The geology of the Iron Cliffs Mine, five miles south-southwest of Penguin, has been described by Burns (1961b). The Rocky Cape Group at the mine consists of sandstone and mudstone, folded into a small anticline of variable plunge with axial trend close to north. The limonite emplacement was post-folding, and from the evidence of nearby areas, pre-Ordovician, so the Rocky Cape Group was here folded in pre-Ordovician time.

At the time of investigation it appeared likely that the steeply inclined dip of Cambrian rocks in contact with the Rocky Cape Group could not have been achieved at any time other than during the folding of the Rocky Cape Group. However the presence of strongly disharmonic folds in the Cambrian on the Penguin foreshore, described in Chapter 7 as abutting against Rocky Cape Group, show that folding of the Cambrian rocks occurred without noticeable deformation of the Precambrian, the contact between the groups acting as a movement surface. In this case, no conclusions can be validly drawn as to the time relations of the folding in the Rocky Cape Group and the Cambrian.

The folding of the Rocky Cape Group at the Iron Cliffs is therefore pre-Ordovician, but either pre- or post-Cambrian. The fold refolds a bedding plane fissility which is analogous to the "bedding cleavage" at Sulphur Creek, so


GEOLOGICAL MAP — SULPHUR
BASS
MAGNETIC
GRID
0
100
200
FEET
TASMANIA

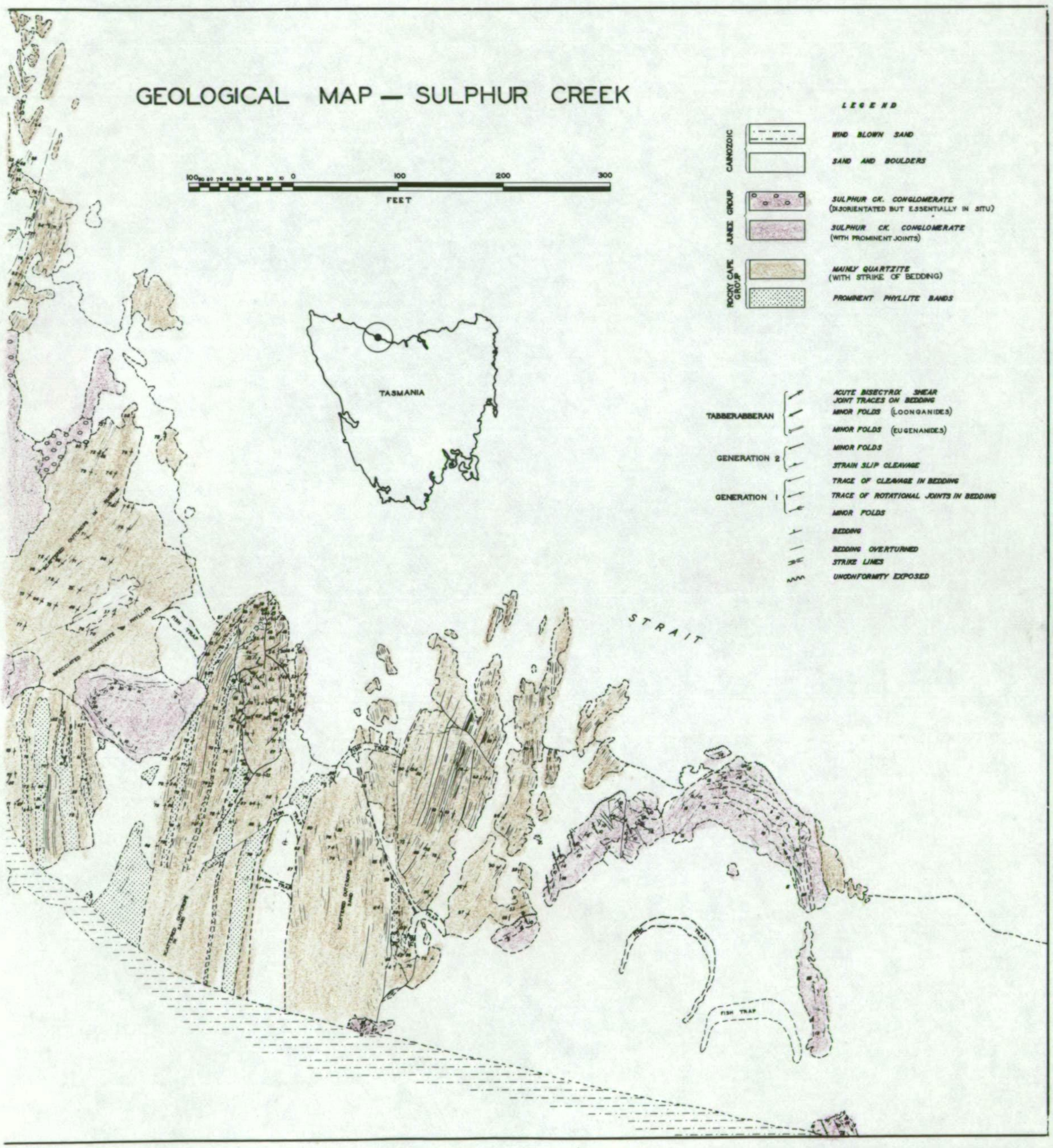

GEOLOGICAL MAP — SULPHUR CREEK
100 90 80 70 60 50 40 30 20 10 0 100 200 300
FEET
TASMANIA
LEGEND
CAINOZOIC
WIND BLOWN SAND
SAND AND BOULDERS
JUNEE GROUP
SULPHUR CK. CONGLOMERATE (DISORIENTATED BUT ESSENTIALLY IN SITU)
SULPHUR CK. CONGLOMERATE (WITH PROMINENT JOINTS)
ROCKY CAPE GROUP
MAINLY QUARTZITE (WITH STRIKE OF BEDDING)
PROMINENT PHYLLITE BANDS
TABBERABBERAN
ACUTE BISECTRIX SHEAR JOINT TRACES ON BEDDING
MINOR FOLDS (LOONGANIDES)
MINOR FOLDS (EUGENANIDES)
GENERATION 2
MINOR FOLDS
STRAIN SLIP CLEAVAGE
GENERATION 1
TRACE OF CLEAVAGE IN BEDDING
TRACE OF ROTATIONAL JOINTS IN BEDDING
MINOR FOLDS
BEDDING
BEDDING OVERTURNED
STRIKE LINES
UNCONFORMITY EXPOSED
STRAIT
FISH TRAP

Figure 48

the fold is probably of the type described as "second generation" at Sulphur Creek, that is, was formed in Precambrian time.

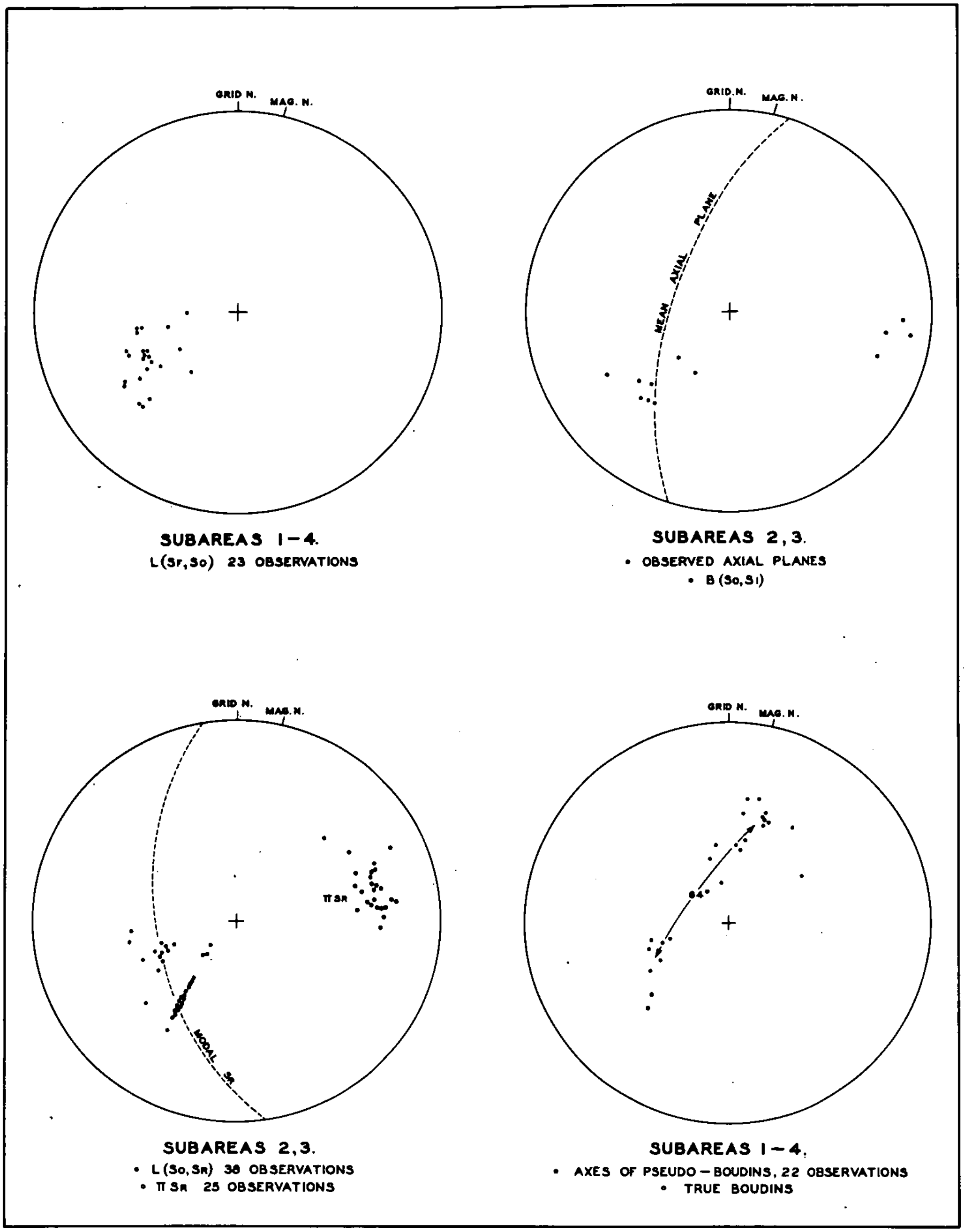
Sulphur Creek

Introduction: The Rocky Cape Group exposed on the headland at Sulphur Creek consists of flaggy bedded sandstone with interbedded phyllite, overlain unconformably by Ordovician conglomerate and sandstone. The unconformity is, in detail, very irregular, with the conglomerate filling hollows in bedrock. Except for minor bedding plane thrusts within the conglomerate, there is the evidence of the "fused" and irregular contact to show that translation along the unconformity has not occurred. Therefore structures of the Rocky Cape Group which do not affect the conglomerate are of pre-Ordovician age.

Four groups of structures are recognised - primary, first generation, second generation, and latestage structures.

Primary Structures: The dominant S-surface is bedding, denoted S_o. The diagnostic feature is the presence of sole markings of several types, including flute casts, frondescent flow casts and syndromous load casts, which were discussed in chapter 1, together with internal evidence, (graded bedding) that the layers are lithogenetic units.

Although there are systematic differences in orientation between the various types of sedimentary lineations, they



First-generation structures, Sulphur Creek

Figure 49

DEPT. OF MINES
2210-29

are grouped together as L_0.

The lithological layering is invariably bedding, which is a diagnostic feature of the Rocky Cape Group.

<u>First Generation Structures</u>: The bedding is folded into tight, almost isoclinal, folds with a strong foliation S_1 in the phyllite parallel to the axial surface. The foliation obliterates the bedding in the phyllite, except for shadow zones in fold cores. $B(S_0S_1)$ fold hinges are scarce at Sulphur Creek, with only three being exposed in subarea 3 (index map, figure 24). The existence of such folds can be deduced from reversals in bedding facing with parallelism of limbs, hence the inferred B(0,1) fold at the boundary of subareas 1 and 2.

The foliation, S_1, is confined to the phyllite. In the sandstone there is a group of related planar and curviplanar structures which are the same age as S_1, but have different orientations and characters.

The principal structures are:

Bedding cleavage, S_b
Fracture Cleavage, S_f
Concentric shear joints, S_c
Rotational shear joints, S_r

Fracture cleavage does not occur at Sulphur Creek, but is common at Blythe Heads, one mile to the west.

Bedding cleavage is a close-spaced planar fissility, subparallel to bedding. The divergence of S_b from S_0 is

Plate 19

Boudinage in interlayered quartzite and phyllite of the Rocky Cape Group, Sulphur Creek.

Hammer handle one foot long.

never more than a few degrees, and is best revealed by beta diagrams constructed on the surfaces. The structure is tectonic, as in one place there can be shown to be numerous cleavage surfaces within a single bed, the bed being a single lithogenetic unit from the evidence of graded bedding. The cleavage was formed in the first generation of folding. In one B(0,1) fold the cleavage wraps around the nose, and is displaced by a crude axial strain-slip cleavage. There are some "true" boudins which "neck down" the bedding cleavage (plate 19).

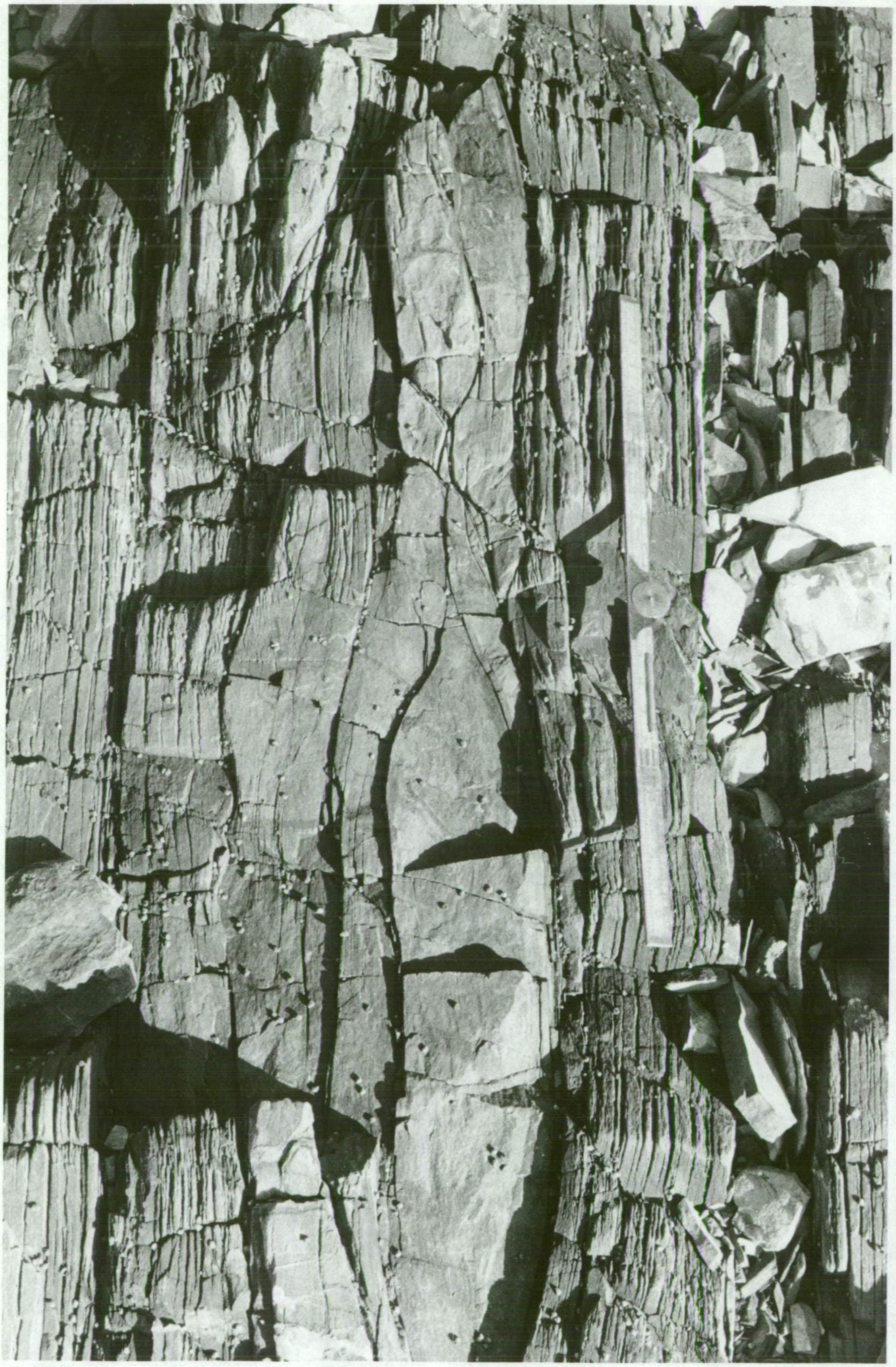
The concentric shear joints (cf de Sitter, 1956, figure 87, p.130) are closely related to the bedding cleavage, but splay and diverge to enclose lenticular areas of sandstone in a pattern reminiscent of boudinage, here termed pseudo-boudinage. The pseudo-boudins outcrop on weathered surfaces as broad swells in S_o. The axes of the swells pitch in two directions at right angles in S_o, as shown in figure 49d and 52b, in a "chocolate-tablet" structure. The relationship of S_c to S_b and S_r shown in plate 21 indicates that the joints are the same age as the bedding cleavage.

Offsetting S_b and S_c are oblique joints, or "rotational shear joints", S_r (cf de Sitter, 1956, p.75). In plate 21, S_b in the sandstone and S_1 in the phyllite are strictly parallel on the left side, this being the limb of a B(0,1) fold. Concentric shear joints outcrop on the right of the

Plate 20

"Pseudo-boudins" in quartzite of the Rocky Cape Group, Sulphur Creek.

Scale is two feet long.



photograph. The central portion has oblique joints, S_r, which are confined to one side of the phyllite band and were thus formed contemporaneously with movement in the phyllite. The plate shows that S_c is younger than, or the same age as, S_r, while S_r is younger than S_b.

Fracture cleavage is rare at Sulphur Creek, but is the dominant structure in the sandstones at Blythe Heads. It is a close-spaced, curviplanar jointing or fissility, which forms sigmoidal curves in the bedding, meeting the bedding at an acute angle. Where S_f is prominent, it forms a well marked and regular linear structure at its intersection with bedding. In such areas S_b is weak or absent.

The several structures described above do not occur simultaneously. Where fracture cleavage is prominent, bedding cleavage and concentric shear joints are absent, and vice versa. Rotational joints are confined to small areas in which pseudo-boudinage and "true" boudinage also occur.

The orientations of structures formed during the first period of folding are shown in figure 49.

Linear structures plotted are the intersection of bedding with fracture cleavage, $L(S_f,S_o)$; the intersection of bedding and rotational joints, $L(S_o,S_r)$; axes of $B(S_oS_1)$ folds; and axes of "pseudo-boudins". There is no significant variation in linear structures between different subareas as the second generation folds are essentially co-axial with

Plate 21

"Rotational joints" in quartzite of the Rocky Cape Group, Sulphur Creek.

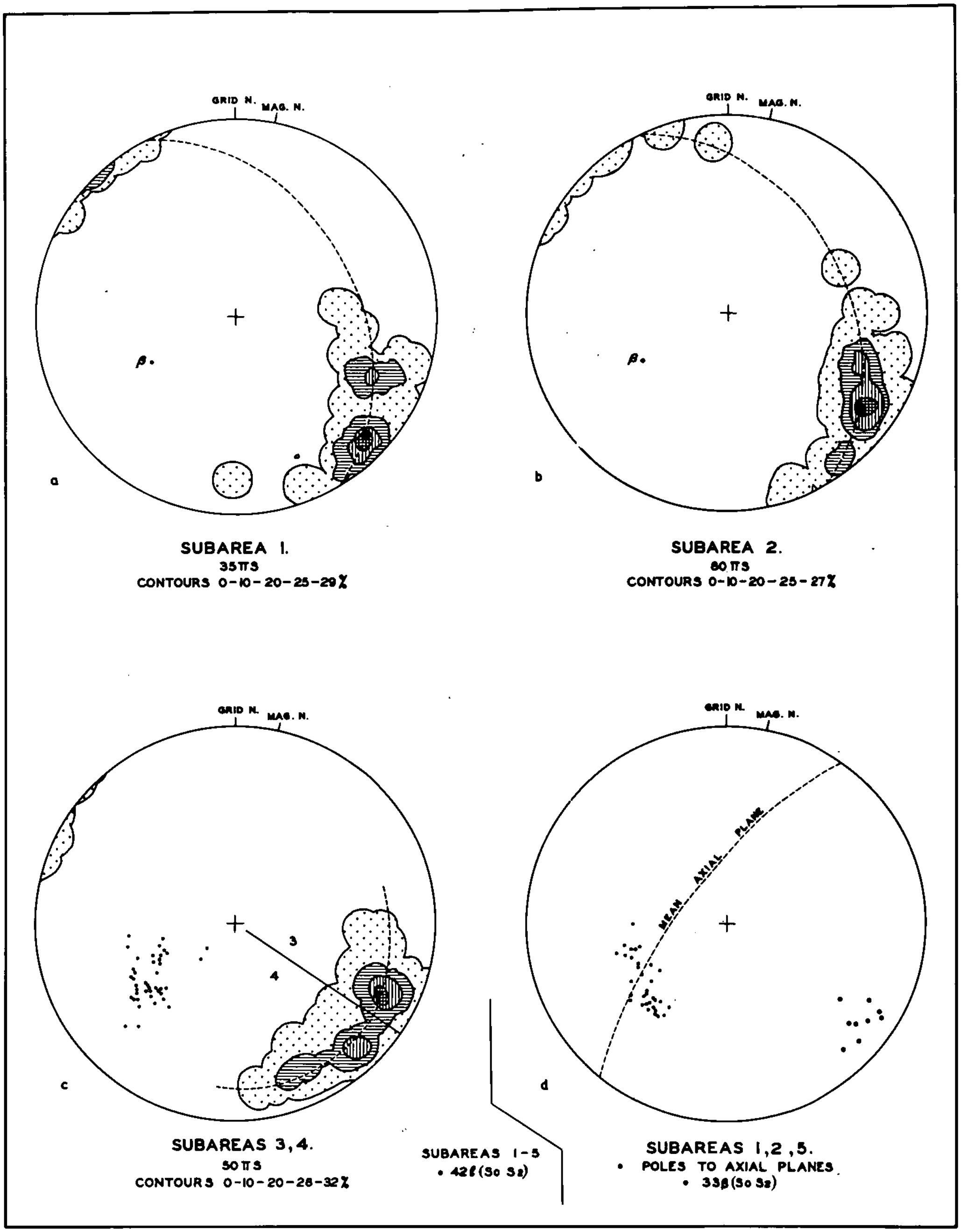
Width of field: two feet.

the folds of the first generation. Planar structures (the axial planes of $B(S_0, S_1)$ folds and the planes of the rotational joints) occur in subareas 2 and 3 and show no systematic variation between the subareas. The planar structure S_b (bedding cleavage) is folded in the same way as bedding in figures 50, 51, and 52; while S_f (fracture cleavage) is folded at Blythe Heads as in figure 53b.

The folds of the first generation at Sulphur Creek have a mean axial plane of 66W016 and an axis pitching 50 degrees south in this plane. R.D. Gee is at present mapping an area extending west from Sulphur Creek and has found (pers.comm.) that the axial distribution is skew. The modal pitch is near 50 degrees as at Sulphur Creek, but the angles of pitch range up to 90 degrees so that many folds are reclined.

Second Generation Structures: Bedding plots for subareas 1-5 yield beta maxima which are essentially parallel (figure 50a,b,c,51d) and coincident with beta maxima measured from single folds in subarea 5 (figure 51a,b).

The folds are open, asymmetrical facing east, with a markedly disharmonic style. The folds in subarea 5 rest on large bedding plane thrusts which bound the folds on the eastern side. The eastern limbs of antiforms are much shorter than the western. Facing of the beds reverses around these antiforms, which have limbs of significantly divergent strike. The beds "young" towards the cores of the folds.



Second-generation folds, Sulphur Creek.
a, b, c: Bedding in areas 1-4.
d: B(0,2) folds.

Figure 50

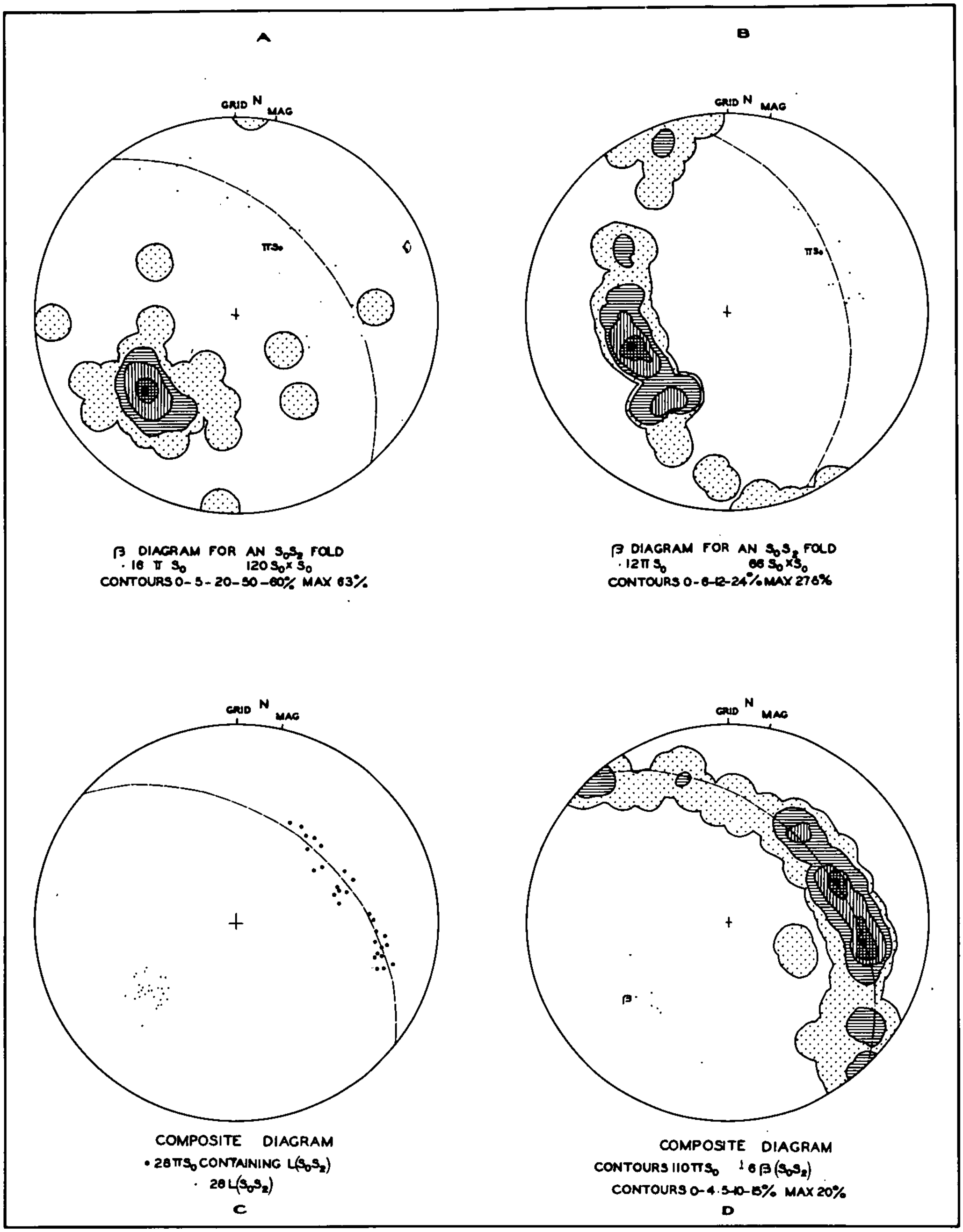
The apparent "synform" of subarea 2 (figures 24,48) is not a fold in the sense that the beds are wrapped around the axis. It is not a synform but two differently-dipping blocks faulted together. The flute casts show the beds maintain a constant facing across the structure.

The fold cores display a crude, widely spaced, strain-slip cleavage, S_2, which crosscuts and crenulates S_0 in the sandstones, and S_1 in the phyllite. In some folds it fans in the core, in others it produces a crude mullion structure.

Folds of this style dominate the structure at Sulphur Creek and are numerous in areas further west. The strongly disharmonic style and constant sense of asymmetry is maintained over wide areas. Many of the folds are not folds so much as drags riding on big strike thrusts. They may be regarded as splay structures in an imbricate movement zone - a type of imbricate or concertina folding.

Several of the major faults and fold closures are overlain by undisturbed Ordovician rocks, showing the movements predate the Ordovician.

Late Structures: The foliation in the phyllite is flexurally refolded on a minor scale. The folds are rounded and open, trending east of south, and correlated with the first generation Tabberabberan; or rounded to conjugate, plunging west, and correlated with the second generation Tabberabberan. (Figure 52). The folds are disharmonic in



Second-generation folds, area 5, Sulphur Creek.
a,b: Beta diagrams for single folds.
c: Linear data from several folds.
d: Bedding from whole subarea and beta from six folds.

Figure 51

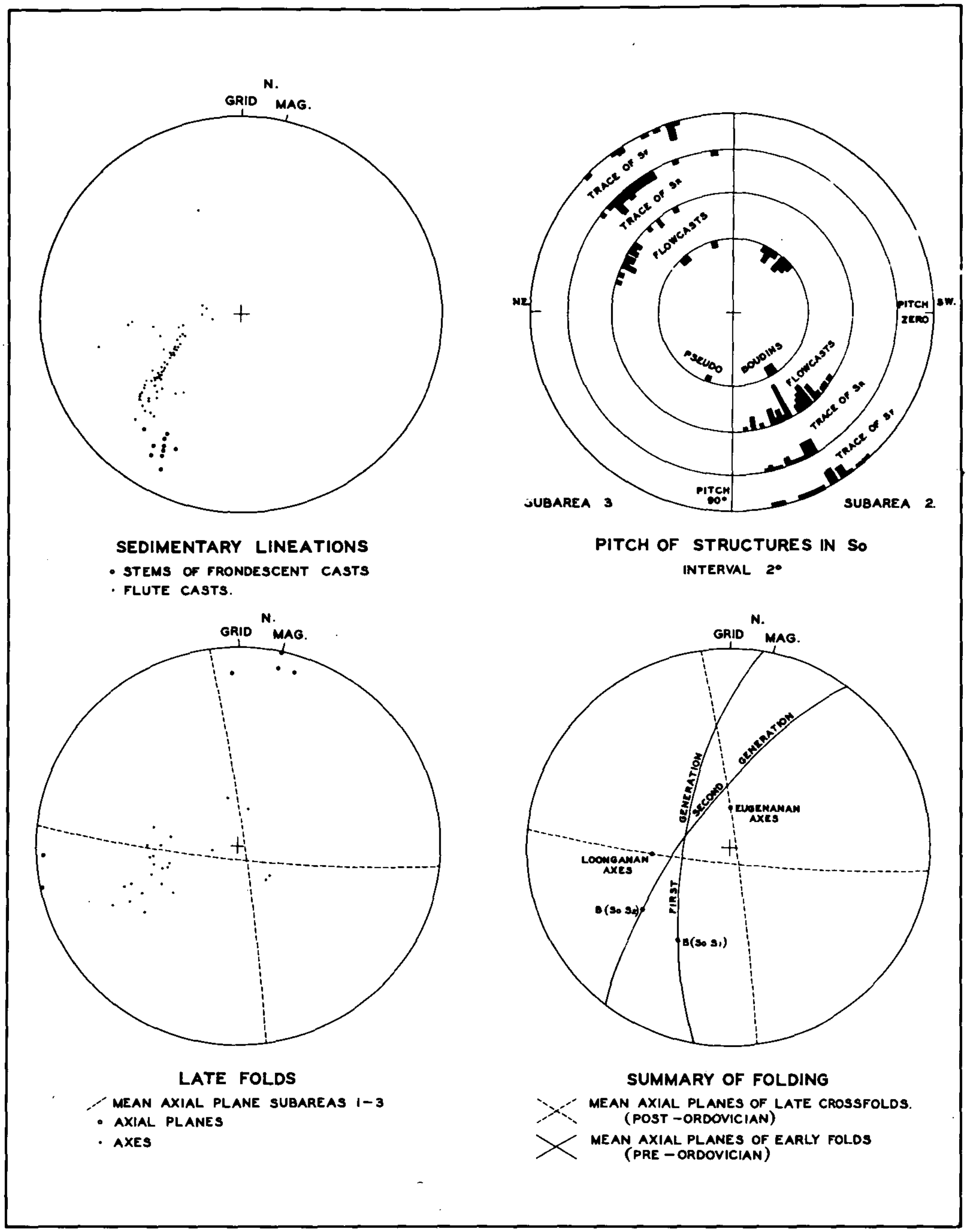
style, restricted to a single wide phyllite band in subarea 2, where they die out against quartzite both up and down in the profile.

The folds are very small, of only a few inches wavelength, and amount to little more than "perturbations" on the Precambrian structure. The strikes of the axial surfaces of these structures accords with the trends in the Ordovician rocks above.

<u>Blythe Heads</u>

The Sulphur Creek area does not contain any linear structures of the first generation refolded by the second. A search was made westwards, along the marine platform, for an area in which fracture cleavage is well developed, with a widespread lineation $S_f x S_o$. This is the case at Blythe Heads, where the fracture cleavage describes sigmoids in single beds, the sigmoids being coaxial with the first generation folding and a uniformly oriented trace of S_f on bedding.

A single, open disharmonic anticline facing east was examined. This structure is identified as second generation as the fold has a style and orientation characteristic of this generation, and contrasting with adjacent first generation folds which have been found in recent work by R.D. Gee to pitch near 90 degrees in S_o. Further, the sense of shear indicated by the fracture cleavage is constant



Sedimentary Structures and late folds, Sulphur Creek.

Figure 52

around the fold, not reversing at the fold hinge as it should if generated in the second folding period. And again, in several places the fracture cleavage is itself crenulated by folds with axes parallel to the second generation structure. (Plate 22).

The geometry is summarised in the stereograms of figure 53. The lineation is not refolded through a large enough angle to determine the refolding mechanism (Ramsay, 1960). However if each segment of lineated bedding is unwound about the B(0,2) axis, the lineation spread is markedly reduced (figure 53d), showing that the lineation is refolded.

This fold is offset by an oblique fault containing a dolerite dyke petrologically identical with the Cooee Dolerite. The latter has been dated radioactively (A.H. Spry, pers.comm.) at 700m. years. This indicates that the second generation folding is older than 700 m. years, that is, Precambrian.

Goat Island

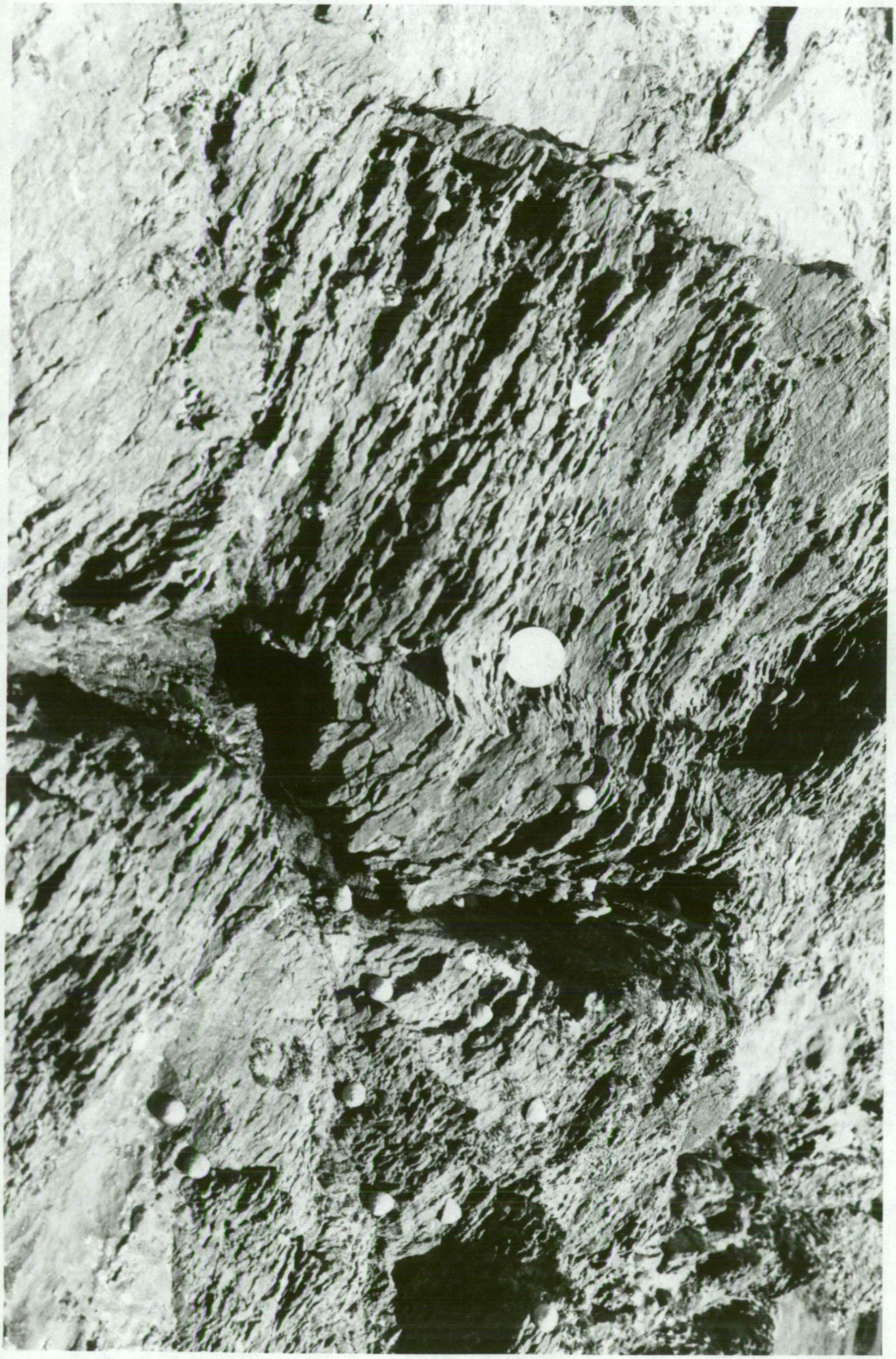
The Tabberabberan structures are weakly developed at Sulphur Creek and Blythe Heads, but are known to be powerful structures both east and west of this area. One such area adjoins Goat Island on the western side (Figure 80).

At Goat Island there are only scattered B(0,1) hinges, but the surfaces S_1 and S_b are well developed. The B(0,2) and (B,2) folds are virtually coaxial in any one place, with

Plate 22

Folded fracture cleavage in quartzite of the Rocky Cape Group at Blythe Heads.

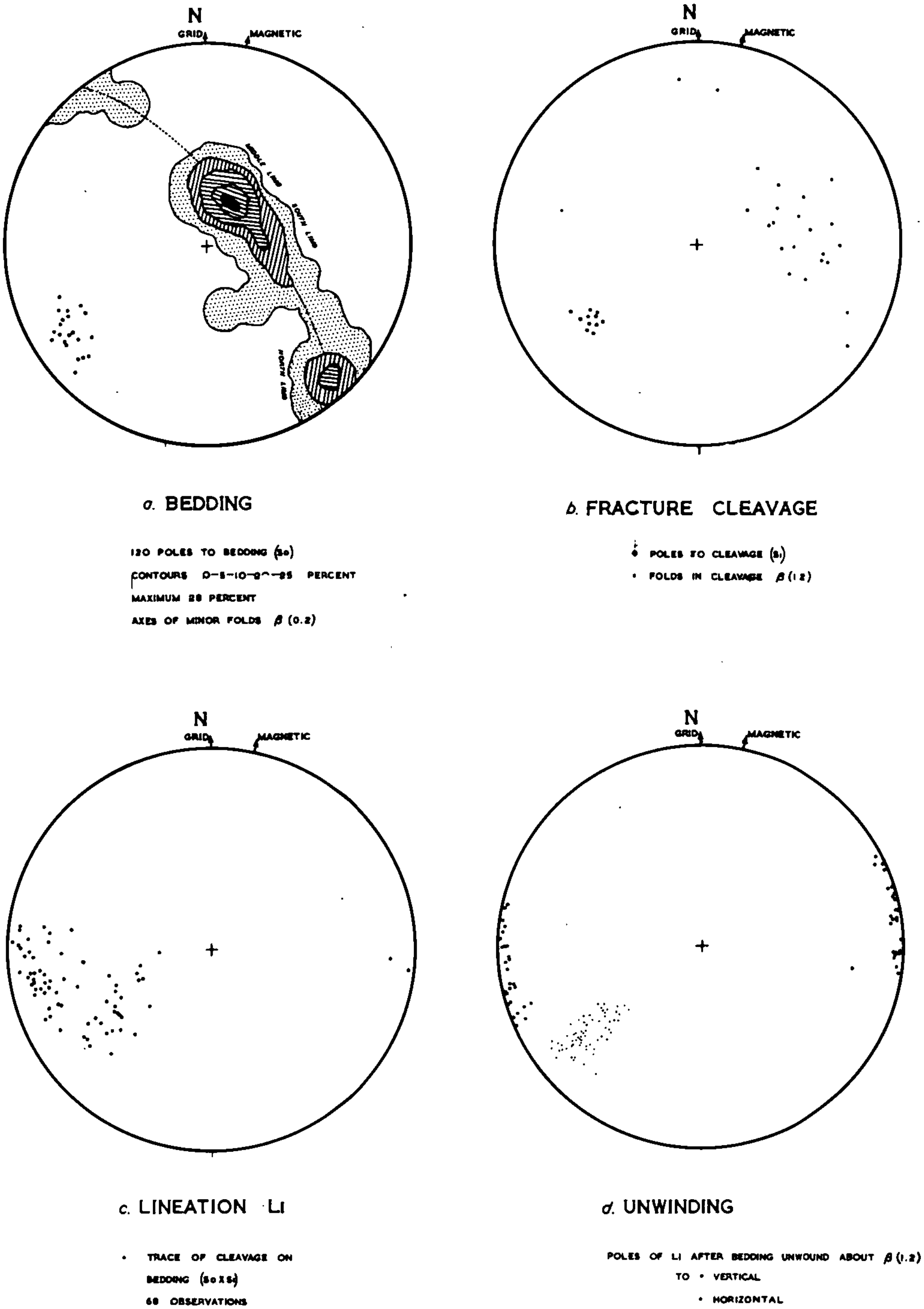
Scale is three centimetres diameter.



a coarse strain-slip cleavage in the fold hinges which in a few folds grades into a crenulation cleavage. There can be no doubt about the time relations of the B(0,1) and B(1,2) folds as in some places, as at "C" in figure 54, the axial structures intersect at high angles.

There is difficulty in distinguishing B(3), the first Tabberabberan folds, from B(1,2) as they have similar styles, with a similar strain-slip cleavage developed. In some places folds of the two phases can be found intersecting, with the crenulation cleavage, S2, offset on a new cleavage, breaking the rock into vertically oriented pencils or cubes. For the maps of figure 54 and figure 80 the folds have been identified on orientation and on the evidence of date provided by crosscutting cleavages.

The second generation Tabberabberan folds (B4) are polyclinal, with two principal axial trends. The area is broken up by north-south strike faults, on which many of these folds rest disharmonically, frequently as symmetrically opposed (conjugate) pairs. The detailed map of figure 54 shows how folds of this generation strongly reflect the earlier structures, being developed only in areas of suitably oriented S_0 or S_1. The folds are weak or absent in limbs dipping east, and best developed in west-dipping beds. The amplitude is a function of lithology. In rocks of strongly alternating lithology, with thin or flaggy bedding, the folds



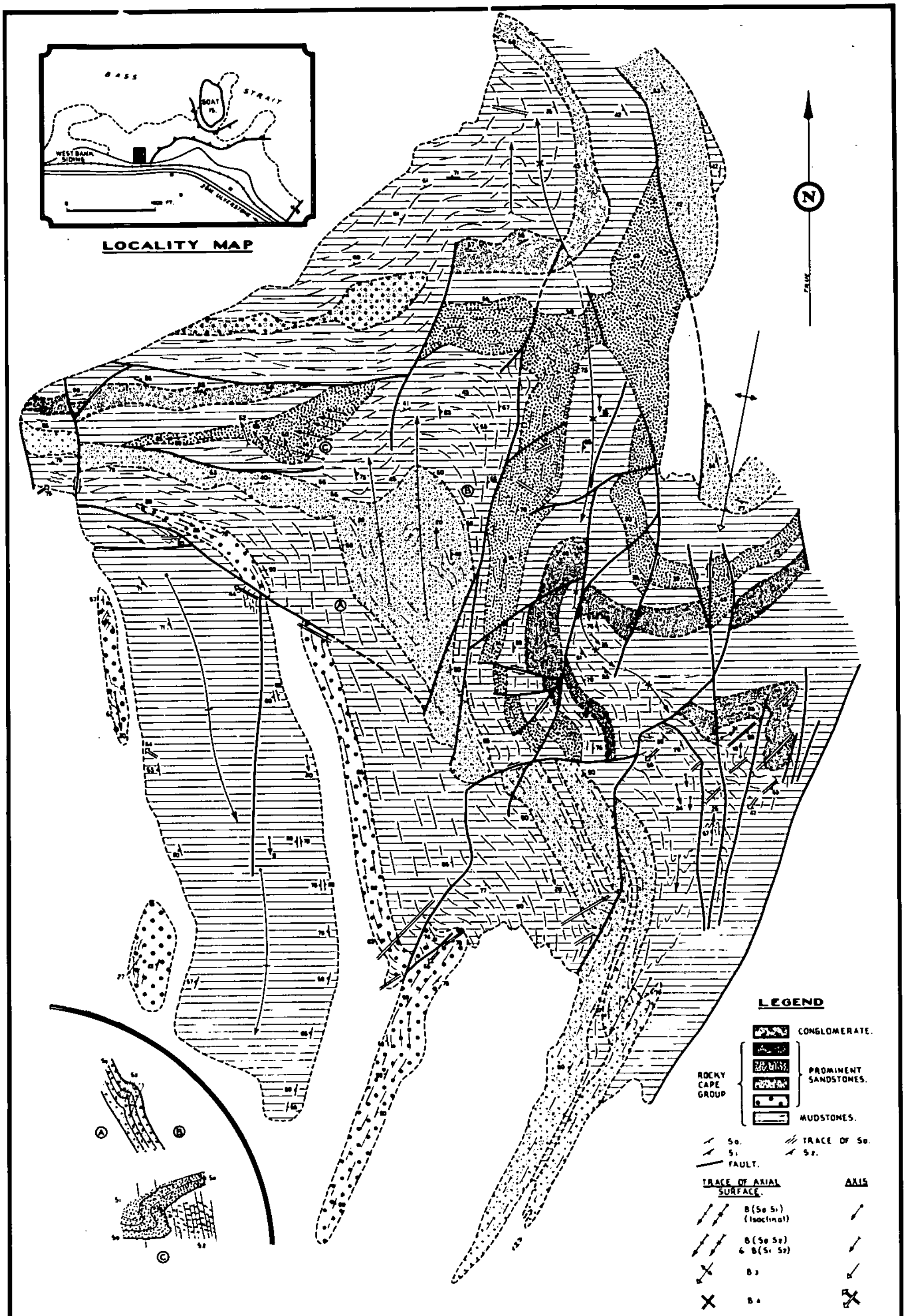
Structures in a second-generation fold at Blythe Heads.

Figure 53

are large, open, and rounded. In very finely layered rock, such as in areas where S_1 is strongly developed, the folds appear as a set of very close-spaced, almost penetrative, crenulations. The axial plunge is a meaningless quantity in these folds, which are superposed with planar axial surfaces, and which therefore have a plunge entirely controlled by pre-existing dips.

The contact between the Rocky Cape Group and Ulverstone Metamorphics is exposed at Goat Island (figure 80). The surface is folded, the folds in the surface coinciding with the polyclinal B(4) folds. The surface is a thrust, as along the base of the Rocky Cape Group there is a confused admixture of Metamorphic schist and conglomerate with mudstone and sandstone. This zone does not appear to be so much a breccia or crush zone as a chaos structure, with the two rock associations infolded, or interpenetrating along imbricate thrusts. As the foliation S_1 of the Rocky Cape Group is found in disoriented boulders in this zone, the thrusting post-dates the first generation folding.

It was indicated earlier that the second generation folding in the Rocky Cape Group has a generally "imbricate" style, possibly related to a major thrust at depth. It is considered likely that the thrust at Goat Island is, in fact, the outcrop of such a thrust. It can be followed for several miles southwards and is folded and disrupted by faults, the



GENERAL GEOLOGICAL MAP

VICINITY OF WESTBANK SIDING

41235 E . 9335 N

Figure 54

folds and faults being identified as Tabberabberan. The thrusting was therefore pre-Tabberabberan. This post-first generation, pre-Tabberabberan age, strongly suggests the thrust belongs to the only major intervening tectonic episode, which is the second generation folding of the Rocky Cape Group.

CHAPTER 9

STRUCTURES IN THE ULVERSTONE METAMORPHICS

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Structures in the Ulverstone Metamorphics

Introduction

The Ulverstone Metamorphics are quartz-muscovite-chlorite rocks which abut against the Forth Metamorphics on the eastern side and underlie Rocky Cape Group on the western side. They extend in a strip from the coast at Ulverstone inland to Spalford (figure 3) but are very poorly exposed away from the coast-line.

At Ulverstone the Metamorphics occur in two, possibly three, basement wedges. The wedges consist of Ulverstone Metamorphics and Rocky Cape Group in association, and have east-facing asymmetry. Rocks of the Dundas Group dip off the western sides while the eastern edges are steep reverse faults which thrust Precambrian over Dundas Group. Attention is confined largely to the western-most wedge, at Goat Island.

A young foliation, S2, is the dominant structure in the Ulverstone Metamorphics. It is a mica foliation in schists and micaceous quartzites which is usually steeply dipping. The continuity of this foliation is established from mapping, and it forms large sweeping curves in plan which are probably due to Tabberabberan folding. The foliation is a transposition surface and controls the major lithological layering. While recrystallisation of mica and chlorite along S2, or transposition to parallelism with S2, has destroyed earlier S-surfaces in many areas, there are inter-folial folds in pelites at Abbotsham and quartzites at Gawler which are formed by a compositional lamination. The S-surfaces earlier than S2 are denoted, collectively, S1, and are preserved only in hinge areas of B(S1, S2) folds.

There is evidence of two phases of folding of the Metamorphics. Structures of only one phase, identified as the second, occur mesoscopically at Goat Island. For this second phase the symmetry of deformation was orthorhombic with axial tendencies and the principal component of strain was an extension in a direction near horizontal and of azimuth near north.

Spalford Area

The boundary between the Forth and Ulverstone Metamorphics is concealed at Spalford but regional mapping shows the boundary is parallel to the transposition foliation S2 which is the dominant structure in the two assemblages.

The Spalford Conglomerate lies about one half-mile west of the eastern edge of the Ulverstone Metamorphics. The conglomerate can be traced as a train of boulders in the soil for a short distance in the vicinity of Spalford. A road cutting in deeply weathered rock shows the conglomerate is a belt about fifty feet wide with margins parallel to S2. There is only one outcrop of indurated (unweathered) rock, on the roadside in Spalford township. This outcrop is about ten feet in diameter.

Pebbles in the Spalford Conglomerate consist of several types of quartzite. Some are white, others red, and some have a black-and-white banding. The pebbles are rounded to subrounded with shapes ranging from spherical to sub-spherical. A few pebbles are platy (oblate ellipsoids) with the flat sides parallel to S2. The matrix is quartz-chlorite schist with a mica foliation curving around the pebbles but generally parallel to the regional S2. Several of the platy pebbles are boudinaged, the manner of boudinage corresponding to vertical extension in S2. Boudin axes are near-horizontal and parallel to the axes of minor B(1, 2) folds of adjacent schists.

<u>Gawler Area</u>

It is probable that the townships of Ulverstone and Gawler are sited on a "basement wedge" with boundary fault running southwest through Gawler.

The wedge consists of a central belt of strongly lineated quartzite, flanked on either side by schist. The lineations are fold mullions and intersections of penetrative S-surfaces. The lineations sweep in an arc convex to the south-east which ends with a sharp twist (in plan) at the base of the Rocky Cape Group. The trend of the foliation in the schist follows the same path. At the boundary, bedding in the Rocky Cape Group is parallel to the foliation in the schist. The twist, which is confined to a zone about 400 yards wide below the contact, is interpreted as due to west-side-south translation at the base of the Rocky Cape Group.

A.H. Spry (pers. comm.) has examined a quartzite from the northeastern end of this belt. The mica forms a weak girdle normal to the lineation with a strong maximum defining the regional foliation, S2. The quartzite has a girdle normal to the lineation, containing a pair of maxima, with an overall symmetry approaching orthorhombic. The mullions are formed by folding of an inherited, passive, mica foliation S1, with the lineations being of S1 x S2 type. S1 is sometimes visible as a colour banding in the quartzite, defining isoclinal similar folds with axial planes parallel to S2.

Picnic Point Area

The quartzites and conglomerates at Picnic Point are being investigated by A.H. Spry. The quartzites are mullioned as at Gawler, with similar microscopic fabric.

Some of the mullions are strongly boudinaged, with boudins on an enormous scale - up to fifty feet long. Being boudinaged mullions, the bodies close in plan and section, forming long contorted spindles or tectonic inclusions. In these Spry (pers. comm.) has found a quartz mortar texture, with different fabrics in grains of different habit. The overall triclinic symmetry may be observed macroscopically in some outcrops with younger lineations superposed on plunging older folds. The inferred kinematic _a_ axis of the youngest deformation is oriented near-horizontal and has an azimuth close to north.

Goat Island

Introduction

The Goat Island fault wedge, forming the hanging wall of the Westbank Fault, consists of Ulverstone Metamorphics and Rocky Cape Group in association. On the western side the wedge is overlain by Dundas Group. The western boundary is a steep unconformity, or a Tabberabberan fault downthrowing west, or possibly both.

The boundary between the Rocky Cape Group and the Ulverstone Metamorphics is interpreted as a thrust. The tidal Goat Island is a window in the thrust, as the structure in the Metamorphics (lower plate) plunges toward the thrust trace, and the bedding in the Rocky Cape Group (upper plate) dips away from it. Immediately above the thrust surface, Rocky Cape Group and Ulverstone Metamorphics occur in intimate association. In places the association is a breccia, with boulders up to twenty feet

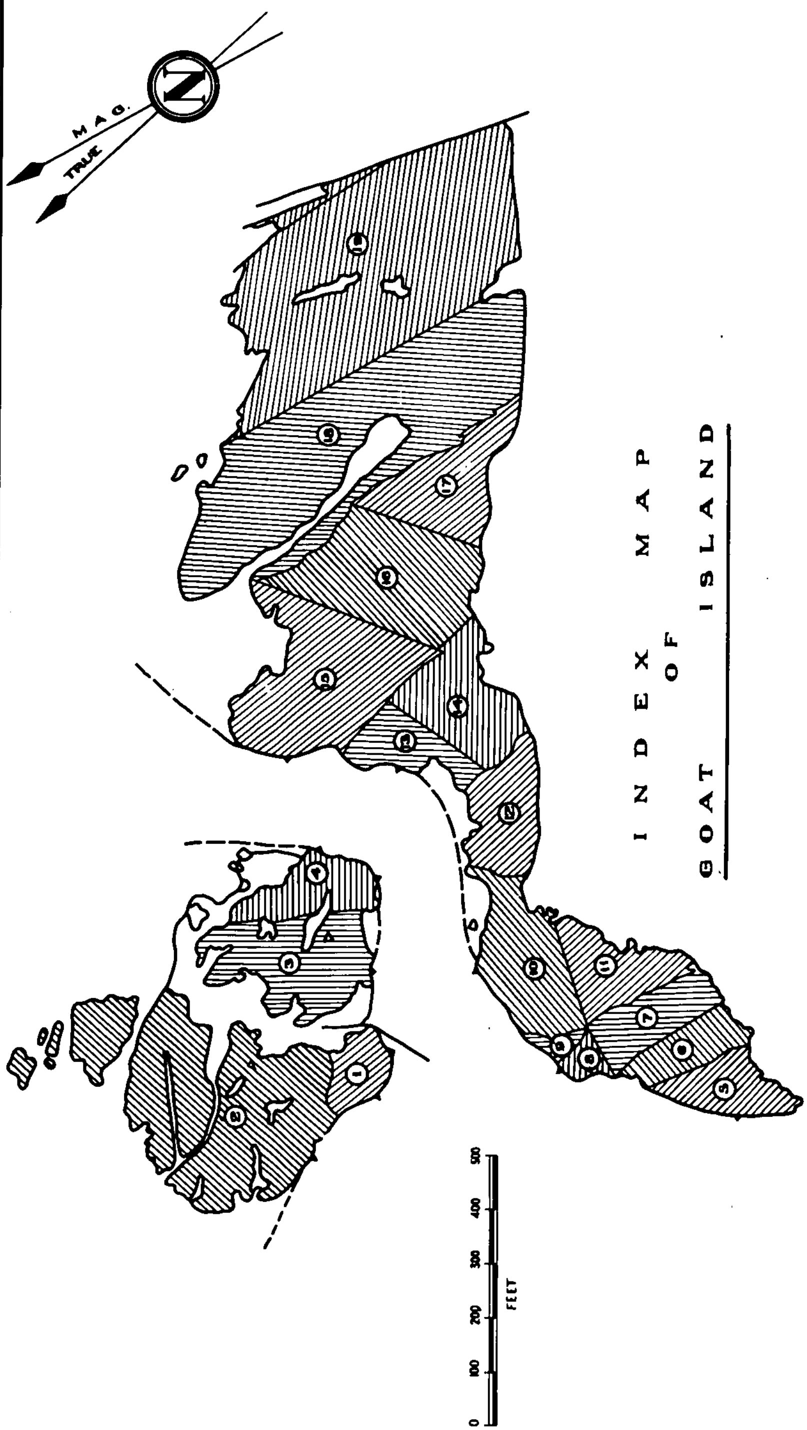


Figure 55

diameter in a patchwork arrangement, in others the two groups may be infolded. The breccia may be tectonic or sedimentary, but the smooth polished boundary between the two rock groups shows that whether the boundary is an unconformity, or purely tectonic, there has nevertheless been considerable movement along it.

Four periods of deformation are recognised in the Ulverstone Metamorphics at Goat Island. The B1 phase is inferred, the only macroscopic evidence being the existence of a quartz-mica foliation and lithological layering, S1, which is probably tectonic. B2 folding is the dominant structure. Superposed as perturbations are the post-metamorphic B3 and B4 folds which are probably Tabberabberan.

B2 structures have been studied intensively in one small area, and two of the principal structural elements of this phase have been mapped throughout the outcrop to outline the later folding.

Measurement of Tecton Shape

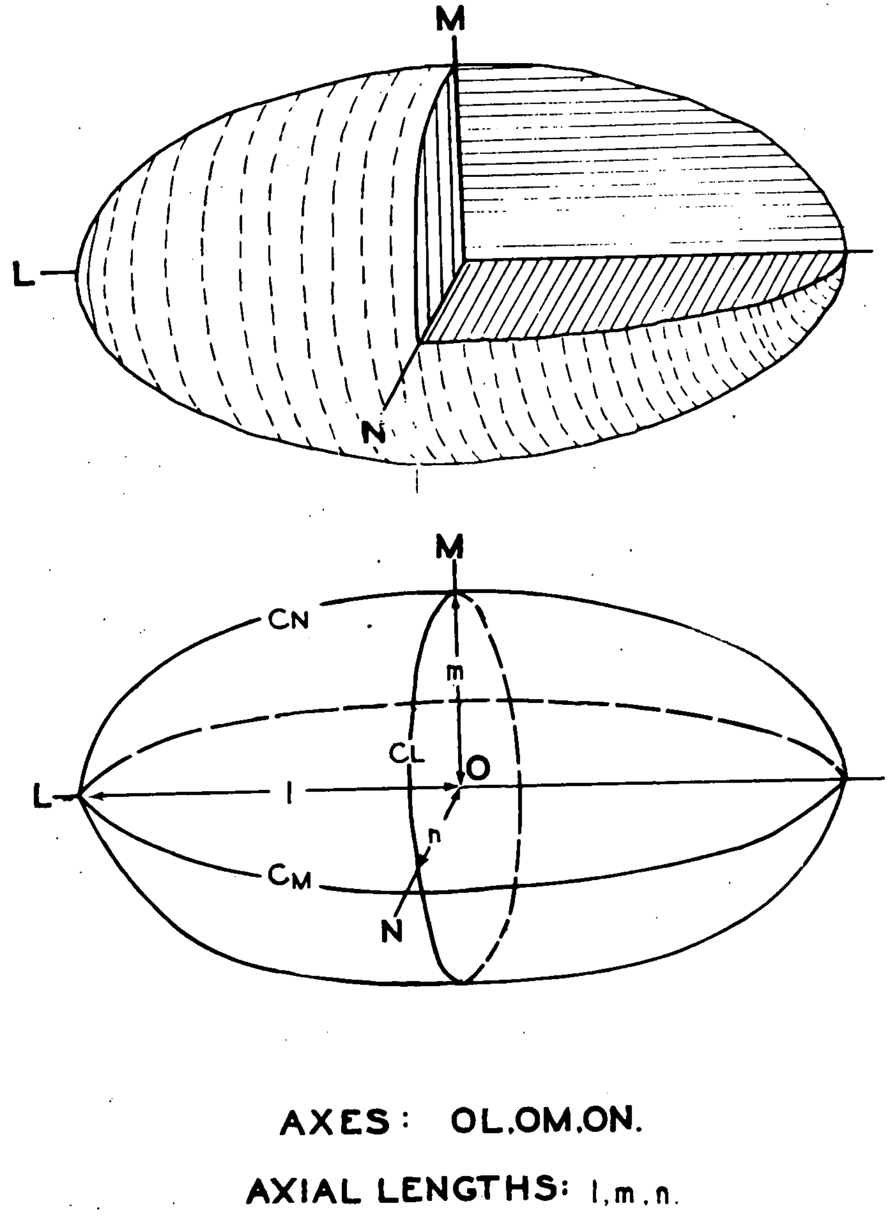
Principal elements of the B2 phase are a foliation, S2, folds of S1, quartz rodding, and the morphological elements of ellipsoidal bodies of quartzite.

The quartzite bodies have the characteristics of a deformed-pebble conglomerate, but will be here termed "tectons". The term tecton is introduced as a general term for a tectonic inclusion, or tectonically formed volume of rock which has a volume or shape as a characteristic feature, in contrast to structural elements which are merely lines or planes. Deformed pebbles, mullions, tectonic fish and tectonic inclusions, are all classed as tectons. While much of the Goat Island Conglomerate is probably deformed conglomerate, there is evidence from Picnic Point that some of the bodies are, in fact, boudinaged mullions, while the occurrence of "nested" tectons shows that the deformation is in many respects a cataclasis or disruption rather than an homogeneous deformation of closed bodies with boundaries which maintain their identity throughout deformation.

The tectons at Goat Island have a shape which is an important element in the rock fabric. In view of this, and their possibilities in estimating amount of strain, a number of tectons were measured in order to determine a statistical shape and orientation.

Two hundred tectons were measured from as small an area as possible. The area sampled is a strip 100 feet long and thirty feet wide on the north-east part of Goat Island, north of the strip of quartzose schist in subarea 2 (figure 55), and has a total depth in profile of less than forty feet.

The macroscopic fabric of this area is summarised in



AXES: OL.OM.ON.

AXIAL LENGTHS: l,m,n.

CIRCUMFERENCES: $C_L.C_M.C_N$.

NOMENCLATURE OF ELLIPSOIDAL TECTONS

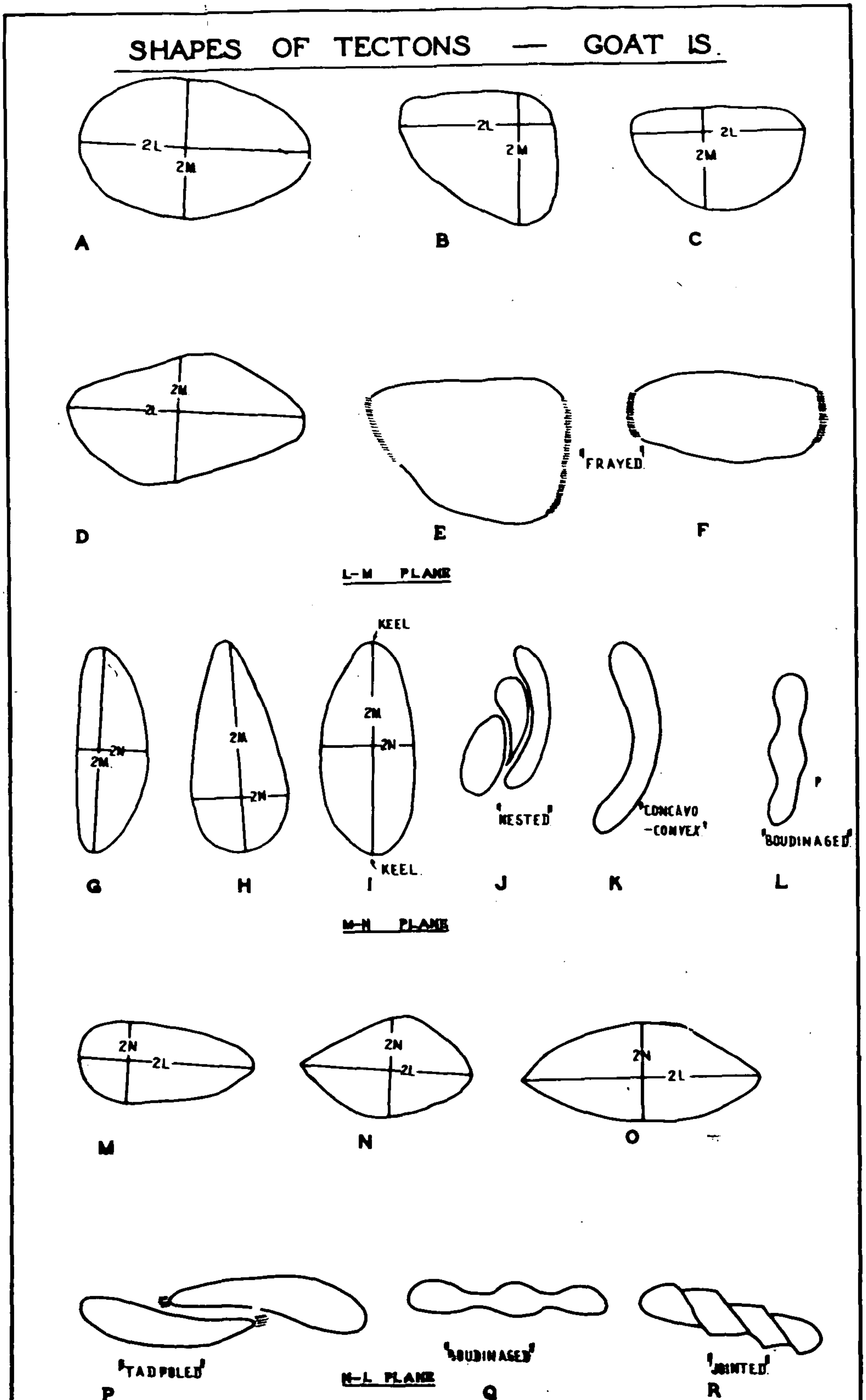
Figure 56

figure 62. The B(1, 2) axes plunge about forty degrees to the south, parallel to the L-axes of tectons (defined below). There is no significant post-metamorphic (Tabberabberan) perturbation of the fabric except for a wide-spaced "ac" jointing. A late Precambrian(?) crenulation cleavage occurs in the quartz schist adjacent to the fault zone which crosses Goat Island but its intensity decreases rapidly away from the fault and the structure is weak, non-penetrative and of insignificant intensity in the area sampled.

There were practical considerations which severely limited the number of tectons measured.

The first requirement was that tectons could be removed cleanly from the outcrop, requiring them to be largely, or at least partly, exposed by weathering. An attempt was made at excavation for buried tectons, in order to restrict the sampling volume, but excavation was found to be impracticable.

Some of the tectons have "frayed" or "shredded" ends, as shown in figure 57. In such cases the boundaries are hard to define, and the tecton is difficult to remove entire, so a second restriction was introduced, namely, that the tectons have rounded ends. Complex shapes, such as the boudinaged forms of figure 57e, q, or jointed tectons, figure 57r, were not measured.


SHAPES OF TECTONS — GOAT IS.
2L
2M
A
B
C
D
E
F
'FRAYED'
L-M PLANE
KEEL
2N
G
H
I
J
K
L
'NESTED'
'CONCAVO -CONVEX'
'BOUDINAGED'
M-N PLANE
M
N
O
'TADPOLED'
'BOUDINAGED'
'JOINTED'
N-L PLANE
P
Q
R
Figure 57

The tecton was removed from the outcrop, the various symmetry planes and axes were determined by inspection and marked on the surface with soft pencil, then each tecton was replaced in its original position in the outcrop and the orientation of some of the elements was determined. A third restriction was introduced here, namely that the tectons could be reinserted and reoriented accurately. This required that no more than two-thirds of the tecton be exposed by weathering.

These practical considerations imposed severe limitations on the number of tectons visible in the outcrop which could be utilised for measurement. Less than one percent of the visible tectons were measured, a total number of 200, with many hundreds being removed from the outcrop but rejected as unsuitable for one reason or another.

A fourth limitation is of a different kind to those discussed above. No satisfactory system could be devised for dealing with tectons with concave surfaces, so measurements were confined to biconvex or planoconvex specimens. This restriction is of considerable importance as thereby is introduced a strong sampling bias. It is estimated that biconvex or planoconvex tectons represent between thirty and seventy percent of the total number of tectons. The measured tectons are representative of a subordinate class of shapes, the convex class.

One hundred tectons were measured in the first instance - the lengths of the three axes, and their orientation. This information was found to be inadequate, so another 100 were measured, with the additional quantities of weight, and the three circumferences.

The nomenclature adopted is illustrated in figure 56. OL is the long axis, parallel to the rodding, and of length **l**. OM and ON are the axes normal to OL, of lengths **m** and **n**, where **m** is greater than **n**.

A codified procedure was followed in identifying the axes.

<u>Axial Directions</u>: The positions of the axes were determined on symmetry considerations. For oblate ellipsoids, the MN plane was identified by the presence of a keel or sharp rim (figure 57i), with OM and ON the long and short axes, respectively, in this plane. The N axis was invariably the shortest, regardless of the attitude of the MN plane, and was readily identified as many of the tectons were platy discs with the flat sides parallel to MN. The OL axis was then located normal to the MN plane.

For prolate ellipsoids, where **m** was nearly equal to **n**, the L axis was readily identified, as in figure 57a, and the MN plane was then located as being normal to OL. The M and N axes were then found by inspection of the MN plane, as before.

Depending upon the general shape, one of these two methods was followed. In all cases the axial directions could be determined unambiguously, with no confusion for intermediate(between oblate and prolate)shapes. The L axis corresponds to the apical line of Lenk-Chevitch (1959), and the method is generally comparable with that he applied to stream and beach pebbles.

Once the axial directions were determined the traces of the planes LM, MN, and NL were marked on the surface of the tecton in soft pencil. In the oblate types, the LM plane was marked first, then the trace of the MN plane around the "bulkiest" part of the tecton.

In the prolate types, a series of traces was drawn of diametrical planes linking the points of emergence of the L axes, and then by viewing the tecton from directions normal to OL, the trace of MN was drawn to meet the first traces at an apparent right angle.

Axial Lengths: The shape of the tectons in the planes LM, MN, and NL was variable. There were symmetrical types (figure 57i, 57o), asymmetrical types (figures 57a, b, c, g, h, m), and subquadrate types (figures 57d, n) in each axial plane.

In asymmetrical types, the axial lengths were measured as the "greatest lengths in the axial direction", as an invariable rule. The method adopted for subquadrate types is explained by figures 57d, 57n..

Usually the axial lengths are such that they decrease in magnitude from **l** through **m** to **n**. However, this is not invariably so, as the axes are defined with regard to symmetry rather than relative length.

__Circumferences__: The circumferences were measured by pulling a linen tape with metallic thread tightly around the tecton, following the marked traces of LM, MN, and NL. The measurements were reproducible, and consistently to within one-eighth of an inch. The necessity for this measurement was one reason for avoiding tectons with concave surfaces, although methods are now available which would permit their measurement.

__Weight__: The weight was measured on a Persinware 14lb spring balance (a high quality household instrument with zero adjustment) to the nearest half-ounce. Large tectons were broken up and weighed in pieces in order to operate the scale in the range of greatest accuracy. This measurement was the last one made on each tecton.

__Orientation__: Orientations were the most difficult measurements to make, as none of the axes are directly accessible.

As has been described, the traces of the axial planes LM, MN, and NL were marked on the surface of the tecton in one colour. The traces of a series of planes through

OL were marked on the surface, in another colour. The tecton was then reoriented in the outcrop.

By examination of the tecton from all aspects, even though the lower end was then concealed, it was possible to visualise the orientation of the L axis and the MN plane in space.

The azimuth of the L axis was measured from above the tecton, utilising the appropriate marked trace. The tecton was then viewed from a direction at right angles, and the plunge estimated with the assistance of other marked traces. Then, by viewing the tecton from the direction of the emergent L axis, the apparent dip of the M axis in the MN plane was measured. For each measurement, the orientation of the Brunton was checked by repeated viewing from several directions.

The accuracy of this method, as with all measurements of inaccessible structural elements, depended upon subjective attributes, such as the ability to visualise the shape and orientation of elements with one end of the tecton concealed in the outcrop, and upon agility, as the Brunton had to be oriented correctly for each measurement, and held firmly while the orientation was checked by observation from several aspects. However, in spite of the subjective factors involved, it was found that measurements were reproducible to within ten degrees, and in most cases to within five degrees, but measurements better than five degrees were difficult to achieve. As shown in figure 62, great accuracy can be achieved with 100 measurements, but it was found that fifty measurements are barely sufficient.

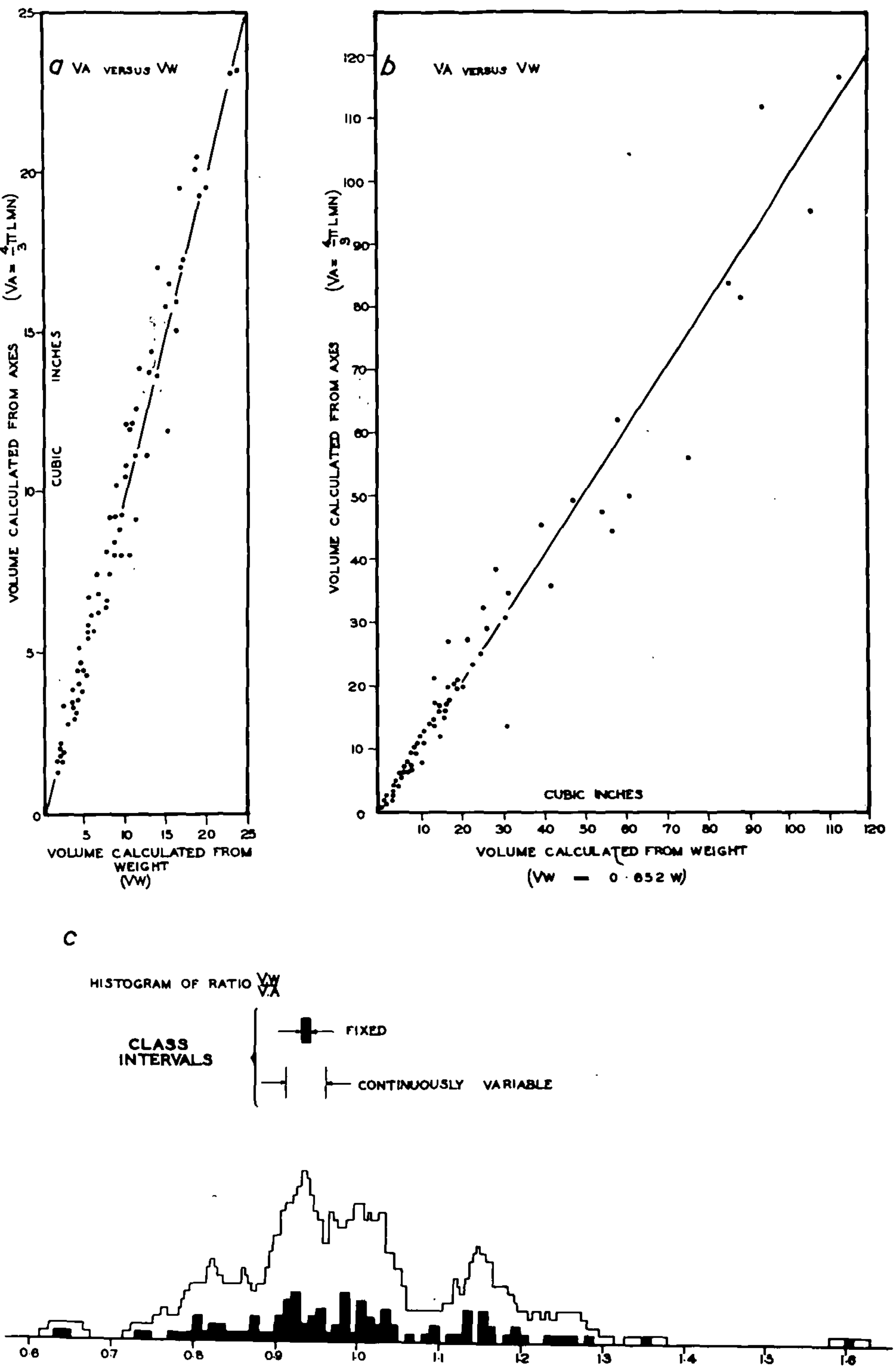
In subsequent general mapping of the conglomerate the orientation of the modal L-axis and the modal LM plane of the tectons was determined wherever possible, as in the general map of Goat Island (figure 80). At each locality the modal orientation of the L-axis was determined by inspection of prolate ellipsoids, and the orientation of the LM plane was estimated from inspection of oblate or platy ellipsoids. The method was found to be generally satisfactory, yielding reproducible results, but could not be applied in areas which were poorly exposed or which had tectons of irregular shape. The "sampling area" for these estimates needed to be about twenty feet diameter and include several hundred well-exposed tectons in order for the estimates to be realistic. This method was therefore only applicable to elucidating large-scale structures. For structures of amplitude comparable to the size of the tectons it was necessary to measure large numbers of tectons at random (as in figure 71) in order to define the structure.

The measurements available are:

Axial lengths	: $2\underline{l}$, $2\underline{m}$, $2\underline{n}$ inches
Circumferences	: C(LM), C(MN), C(NL) inches
Weights	: W ounces
Orientation of L	: Plunge and azimuth, degrees
Pitch of M in MN	: Degrees

Calculations of two kinds were made. First, for verification of the measured axial lengths, the axial lengths were used to calculate the volume and circumference of each tecton. Comparison of the measured with computed values of these quantities provides a check on the accuracy of measurement. The calculations are based on an ellipsoidal form, so there should be a systematic lack of agreement for certain shape classes. Second, a search was made for quantities which the tectons have in common, on the assumption that quantities common to the tectons irrespective of the shape class must be significant.

Volumes: Three tectons were carefully weighed in the laboratory, and their volumes measured from a water displacement apparatus constructed by N. Ahmad for investigations of the size of boulders in glacial deposits. It was found that the water displacement method gave variable results, estimates of specific gravity ranging from 2.56 to 2.70, averaging near 2.62, which is low for quartz and muscovite. A mean figure of 2.655 was finally adopted. On this basis, one ounce of tecton occupies 0.652 cubic inches.



WEIGHT RELATIONSHIPS OF TECTONS

N E GOAT ISLAND

99 OBSERVATIONS (101 - 200)

Figure 58

The "volume from weight", $V(W)$, was computed as

$$\underline{V(W) = 0.652\ W} \quad \text{cu.ins}$$

The volume was calculated from the axes on the assumption that the tectons are regular ellipsoids. The "volume from axes", $V(A)$, was computed as

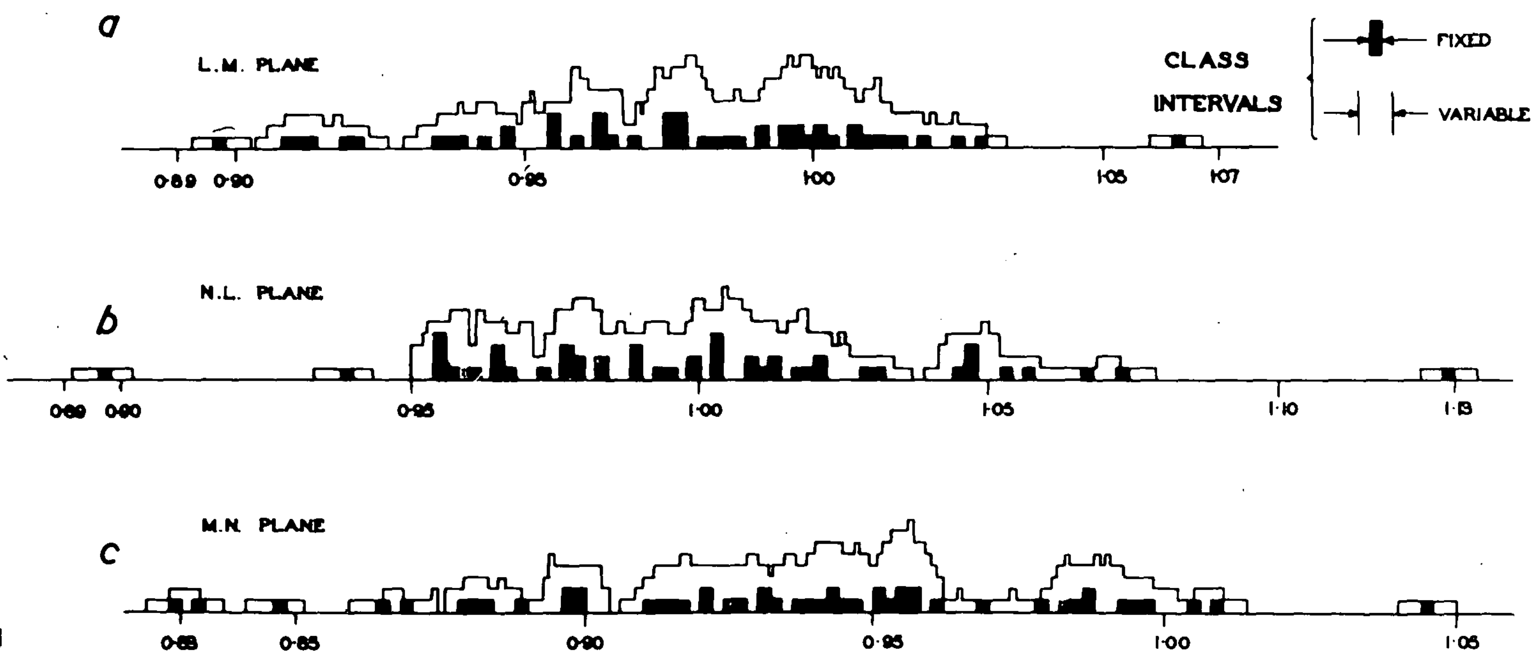
$$\underline{V(A) = \frac{4}{3}\pi\, lmn} \quad \text{cu.ins}$$

Comparison of V(A) and V(W) in figures 58a and 58b shows that there is good agreement. The histogram of the ratio V(W)/V(A) in figure 58c has a mean of 1.0053.

This result shows that V(A) is an accurate measure of volume for the mean value, with errors of less than thirty percent in all but a few rare tectons, and less than twenty percent in eighty-six percent of the tectons. The product **lmn** can therefore be used as a measure of size.

The subsidiary modes in figure 58c are probably certain shape classes. The mode at 1.0 is ellipsoids, those at 0.825 and 0.935 are asymmetrical tectons, the former probably those with swollen ends (figure 57h, 57m), the latter those with one side flattened (figure 57b, c, g). The peak at 1.145 is probably those of subquadrate form (figure 57d, n).

It is emphasised that this is a statistical result. The quantity V(A) is a measure of volume for an individual tecton only when it has a very regular form. When a large number of varied shapes are considered, the ratio



HISTOGRAMS OF RATIO $\frac{\text{CALCULATED FROM AXIS}}{\text{MEASURED}}$ FOR CIRCUMFERENCES OF TECTONS

N.E. GOAT ISLAND

50 OBSERVATIONS (NUMBERS 101-151)

Figure 59

V(W)/V(A) is unity, that is, the mean shape is ellipsoidal - not for instance, a bicone.

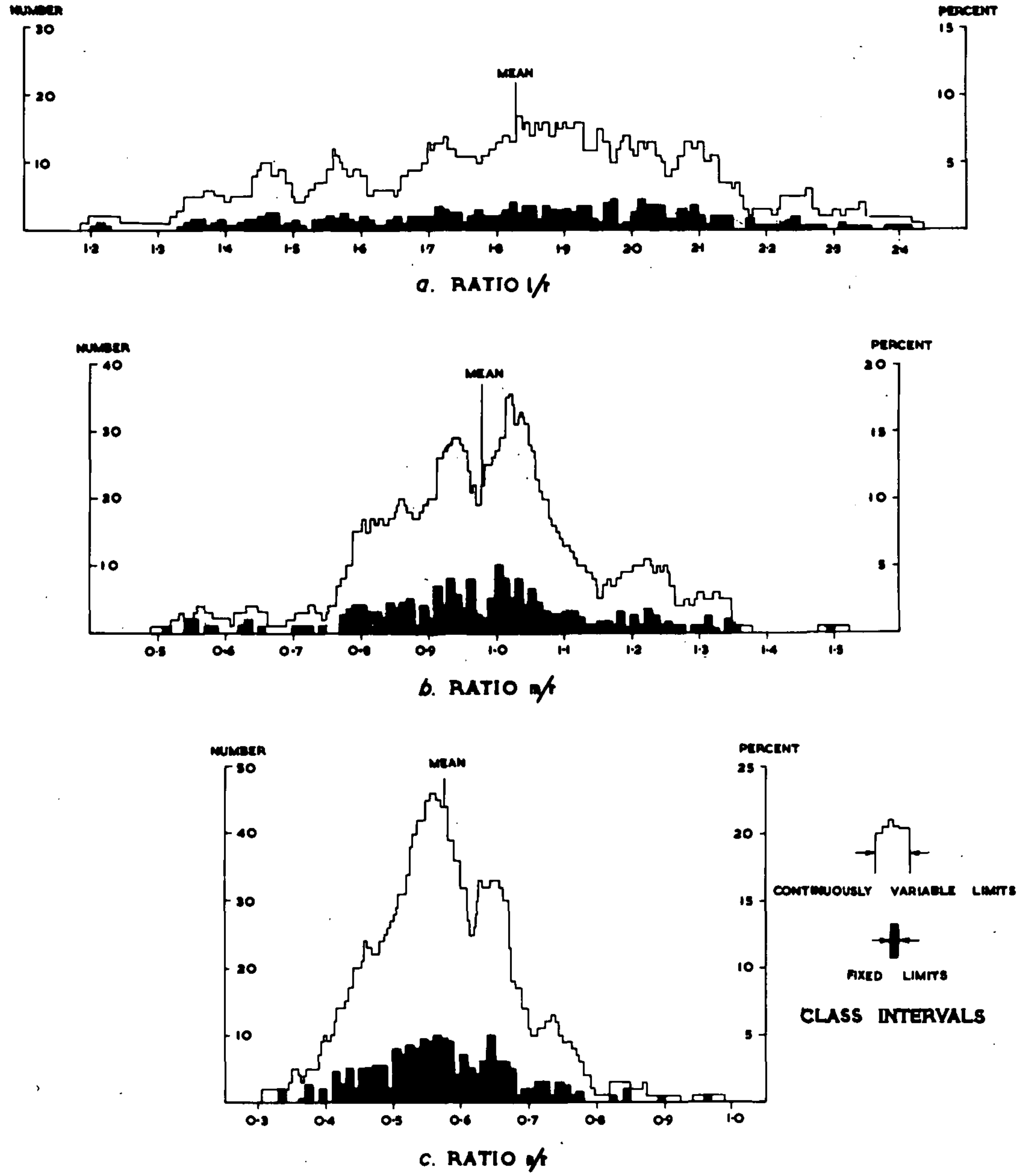
<u>Circumferences</u>: To avoid the possibility of error in the conclusion that the mean shape is an ellipsoid, the circumferences were calculated from formulae of the type

$$C(LM) = 2\pi\, l \left\{ 1 - \frac{1}{4}e^2 - \frac{3}{64}e^4 - \frac{5}{256}e^6 \right\}$$

as in Caunt (1914, p.306). Higher terms of the power series were neglected as insignificant. The quantity e in the equation above is the eccentricity in the LM plane. Analogous formulae were used for the other axial planes.

Comparison of circumferences, as calculated, with those as measured, is plotted for fifty tectons in figure 59. The pattern is similar to that for the volumes and confirms that the mean shape is an ellipsoid.

<u>Axial Ratios</u>: It has been shown that the quantity V(A) is a suitable measure of volume. The produce lmn is therefore a suitable measure of size. Tectons of different sizes may be compared, therefore, by comparison of the axial ratios $\frac{l}{r}$, $\frac{m}{r}$, and $\frac{n}{r}$, where $r^3 = lmn$. The quantity r may be thought of as the radius of the unit sphere of volume equal to the tecton. The axial ratios are introduced solely as a convenient way of comparing the shapes of tectons of different sizes - no genetic implications are involved in the use of r. It is not



FREQUENCY HISTOGRAMS SHOWING

AXIAL LENGTHS OF UNIT TECTONS NE GOAT ISLAND

RATIO	MEAN	MODE
l/r	1·83	1·83
m/r	0·98	1·02
n/r	0·57	0·55

Figure 60

assumed, for instance, that the tectons are deformed spheres.

Two hundred observations of the axial ratios are plotted in figure 60. In terms of mean values, $\frac{l}{r} = 1.83$; $\frac{m}{r} = 0.98$; $\frac{n}{r} = 0.57$. In each case this result is plus or minus about 0.03, the figure 0.03 being obtained from comparison of the product lmn for various modes. This yields the result:

$$\underline{\frac{l}{r}:\frac{m}{r}:\frac{n}{r} = 1.87:1:0.582 \quad \text{(Mean values)}}$$

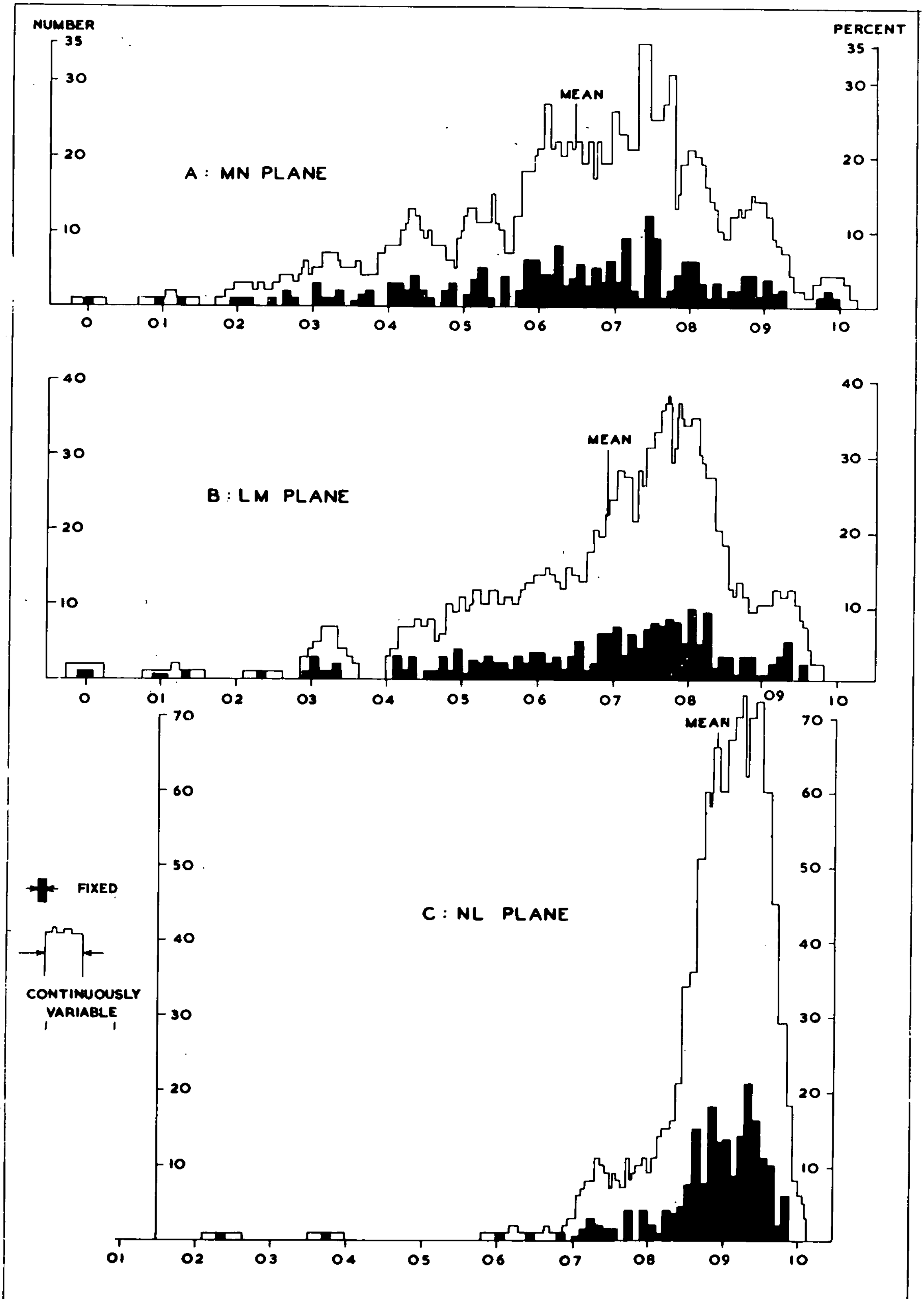
The modal values for n/r and m/r are well defined at 0.55 and 1.02 respectively. However, the corresponding l/r is difficult to locate. A mode between 1.9 and 2.0 can be found in figure 60 using larger class intervals than those shown in the figure, but cannot be located with precision. The result, therefore, is that

$$\underline{m:n = 1:0.54 \qquad \text{(Modal values)}}$$

Eccentricities: The shape of the tectons may be expressed in terms of the eccentricity in each axial plane. The eccentricity, e^2, was calculated for each plane using formulae of the type

$$e^2(LM) = 1 - m^2/l^2 \qquad \text{(in the LM plane)}$$

In figure 61 the results of observations numbers 101-200 are plotted, excluding No.142 from 61a, Nos.112, 162, and 134, from 61b. The eccentricities are independent of size.



ECCENTRICITIES OF TECTONS GOAT ISLAND

Figure 61

It will be noted that the eccentricities are more sharply defined than the axial lengths, and presumably more significant. The subsidiary modes due to shape classes are suppressed. The eccentricities are sharply defined in the NL plane, less so in the LM plane, and least in the MN plane.

Mean values are for $\underline{e}^2$:

LM plane: 0.69 MN plane: 0.65 NL plane: 0.89

from which it may be calculated that

$$\underline{\underline{\underline{l}:\underline{m}:\underline{n} = 1.79:1:0.59 \quad \text{(Mean values)}}}$$

Modal values are for $\underline{e}^2$:

LM plane: 0.77 MN plane: 0.74 NL plane: 0.94

from which it may be calculated that

$$\underline{\underline{\underline{l}:\underline{m}:\underline{n} = 2.08:1:0.51 \quad \text{(Modal values)}}}$$

The shapes of the tectons are classed as follows:

1) Symmetrical
2) Asymmetrical
    a) One end bulbous
    b) One side flattened
3) Subquadrate
4) Complex (nested, tadpoled, boudinaged)

It may be noted that types 1, 2b, and 3 occur in pebbles abraded by a fluid (Lenk-Chevitch, 1959) so that the occurrence of types 2a and 4 are probably the criteria of tectonic deformation.

The measurements were made by a method which has the effect of treating tectons of shapes 2 and 3 as if they were of shape 1. This causes the skew distribution of quantities in the frequency diagrams. Tectons of shape 4 were not measured.

There is a deviation of the mean from the mode in measurements of shape quantities. The modal value is assumed to represent ellipsoids. That this is not also the mean reflects the skew distribution, and the fact that shapes on one side of the mode are more likely than shapes on the other.

The frequency histograms of eccentricity and axial ratios provide fundamental information about the shape. On general grounds, it might be expected that if any quantity is genetically important, it should yield a strong maximum in a frequency diagram. The maxima are as follows (class interval 0.05),

<u>Eccentricity</u>:	NL plane	73 percent
	LM	38
	NM	35
<u>Axial Ratios</u>:	$\underline{n}/r$	23
	$\underline{m}/r$	18
	$\underline{l}/r$	18.5

The most significant quantity is $\underline{e}^2$(NL).

It is not possible to follow the methods used by Oftedahl (1948). Deformation of the rock was not homogeneous, there is evidence that volume was not preserved in individual tectons, and the assumption of an original spherical or ellipsoidal shape cannot be made. However, speculations of another kind are possible.

For instance, the very marked concentration of eccentricities in the NL plane around a value of 0.94 shows there is a strong tendency for the ratio l:n to be fixed near 4:1. If there was a plane strain in LM tending to fix this ratio, the ratios of m:l or m:n could vary at will, even under conditions of constant volume. The concentration of eccentricities in the LM and MN planes indicates that this does not occur, and that in fact the value of m relative to the other axes tends to be fixed. This implies that strain was three-dimensional, as indeed was the case with the Norwegian tectons examined by Oftedahl.

Discussion of the significance of the tecton shape is given below, in conjunction with other fabric elements. However, it may be noted that the significance of the tecton shape rests not with its value as an index of bulk strain or with its deformation from some early unknown shape, but in the shape as an indicator of equilibrium conditions during deformation. The proximity of the axial lengths to the ratio 4:2:1 is highly significant in this respect, and the original shape largely immaterial.

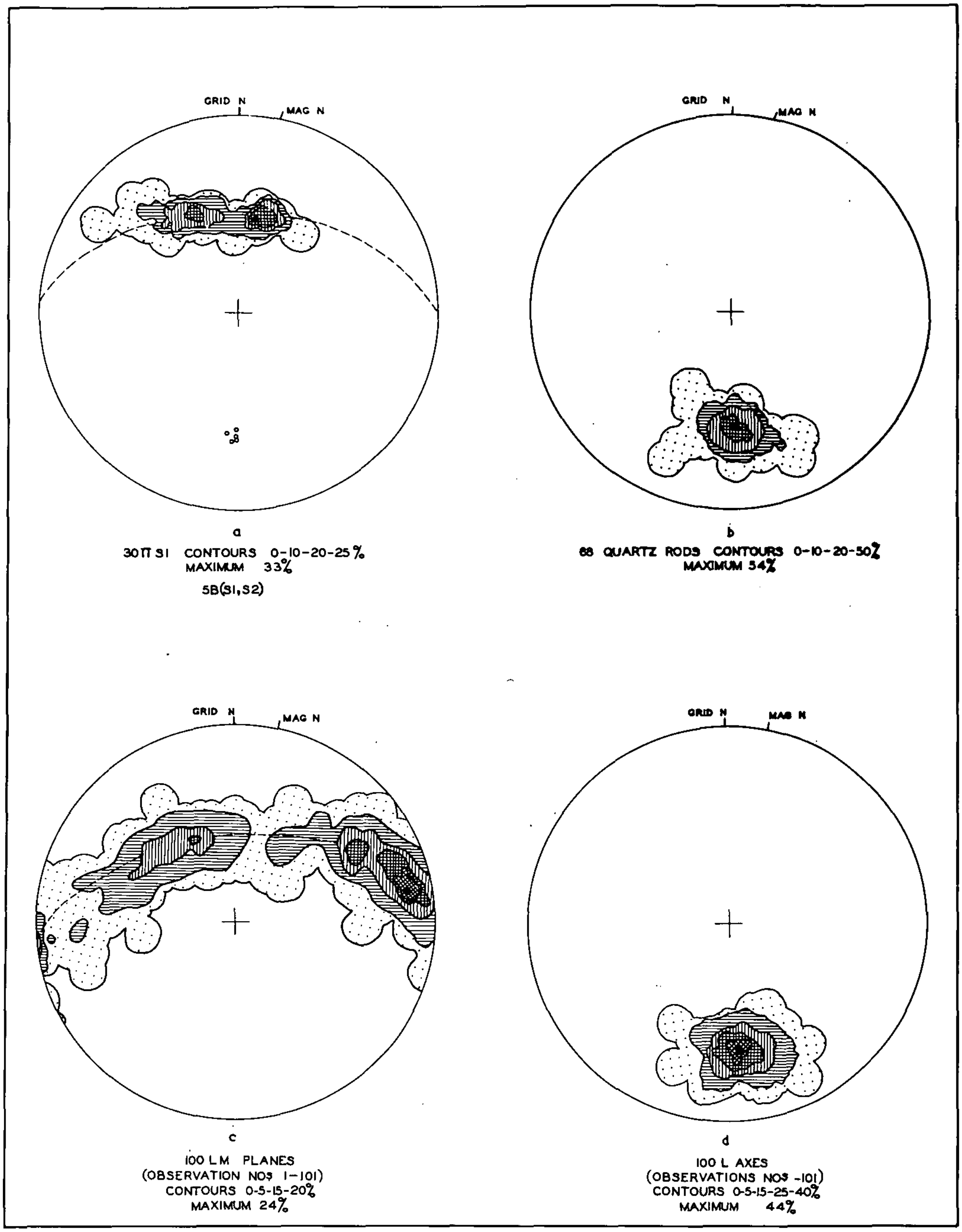
Structures of the B2 phase

The orientation of the tectons may be specified in terms of the L-axis and the LM plane. In the conglomerate at Goat Island, other mesoscopic fabric elements include the foliations S1 and S2, the axes of B(1, 2) folds, and the axes of quartz rods.

The fabric of area 2 (see index map, figure 55) is considered in detail. The geometry of the structural elements is shown in figure 62. The early foliation, S1, is rotated into the small folds of plate 23, with the axis of the S1-pole girdle oriented 39-183 (figure 62a). Thin layers of milky quartz lie subparallel to S1 in the quartz schist and are found in the matrix of the conglomerate. They are strongly folded into tight "rods" with a modal axial orientation of 42-179 (figure 62b). The axial surfaces are not regularly oriented but have variable attitudes, many being curved (plate 24). The axial surfaces probably form a sheaf co-axial with the axes. Rods occur within the conglomerate, those observed having a mean orientation parallel to the rods in the quartz schist.

The L-axes of tectons yield a strong maximum oriented 36-176 (figure 62d). Identical results were obtained from two subfabrics containing 100 L-axes in each.

Poles to the LM planes of tectons yield a girdle with the axis of the girdle oriented parallel to modal L



Structures in area 2, Goat Island

Figure 62

(figure 62c). This exact parallelism is not derived independently but is a consequence of the method of measurement of LM. The feature of interest in figure 62c is not the orientation of the girdle but the distribution of LM-poles within the girdle. The highest-value mode corresponds to a dip of 76SW170 which is identified as S2. The subsidiary mode is ninety degrees removed from this orientation.

The foliation S2 is only weakly developed in the quartz-schist of subarea 2. It cannot be satisfactorily determined in the matrix of the conglomerate. However, the modal orientation of S2 in other areas corresponds closely to the modal orientation of LM planes of tectons.

The dimodal distribution of LM planes is of problematical significance. Measurements were made with reference only to the symmetry of each individual tecton and M was defined as the longest axis in the plant MN. However, if M had been defined with reference to the tectons as a group (perhaps as the axis in the MN plane lying nearest to S2) then a unimodal distribution could have been obtained. Tectons contributing to the subsidiary mode have a prolate form.

Regardless of the significance of the subsidiary mode, there is a spread of M axes to form a complete girdle.

The mesoscopic imposed structures of area 2 have

Plate 23

B(1, 2) folds, area 2, Goat Island.

Width of outcrop five feet.

orthorhombic symmetry with axial tendencies.

B(1,2) folds with wavelengths between six inches and two feet have parallel axes (figure 62a). The distribution of S1-poles in figure 62a shows that the B(1,2) folds are symmetrical with parallel bisecting surfaces. The B(1,2) axes and bisecting surfaces have, in combination, orthorhombic symmetry.

The quartz rods occur in defined layers within the quartz schist, and in the matrix of the conglomerate. The polyclinally-folded quartz rods have parallel axes (figure 62b) which are parallel to the B(1,2) axes. Planar portions of the axial surfaces of the polyclinal folds form a sheaf which has axis parallel to the axes of rods (plate 24). The axes and axial surfaces define an imposed axial subfabric.

The mica foliation in the schist forming the matrix of the conglomerate is folded (figure 63a). The axes of the folds are parallel to the B(1,2) axes. The axial planes "wrap around" large quartz grains but tend to be parallel to S2. The axes and axial surfaces together define a probably orthorhombic subfabric. The behaviour of the quartz rods in the matrix of the conglomerate is similar.

The movement picture is considered to have orthorhombic symmetry with a tendency towards axial symmetry with the infinity-fold axis parallel to the B(1,2) axes.

On the scale of the thick layering in the quartz schist, S1 was kinematically active, so that the final fabric of folded S1 has only those symmetry planes common to the layering and the movement picture (cf. Paterson and Weiss, 1961). The two "causes" (S1 before folding and the movement picture) have axial symmetry with infinity-fold axes almost perpendicular to each other so the final fabric is orthorhombic. The quartz laminae in the "polyclinal layers" were deformed passively and have a higher symmetry in consequence.

Within the quartz schist the different layers are thus different "domains of deformation" in the sense of Weiss (pers. comm., Canberra Symposium, 1962). The domain boundaries are the coarse lithological layerings parallel to S1 which were presumably active during deformation.

The L-axes of tectons are statistically parallel to the B(1,2) axes. The LM planes form a sheaf about this direction with a central maximum and a subsidiary maximum being ninety degrees apart (figure 62c). The subfabric resulting from the combination of these elements has orthorhombic symmetry.

Although the mesoscopic structures have high symmetry, the grain fabric is triclinic.

The optic axes of quartz grains were measured in two planes at right angles in a specimen of schist from the matrix of the conglomerate. Rotated into parallelism the partial fabrics have the same pattern so the two sub-fabrics

Photo 24

"Bedding" in quartz layers, area 8, Cont Island.

Looking south.

Scale: three centimetres.

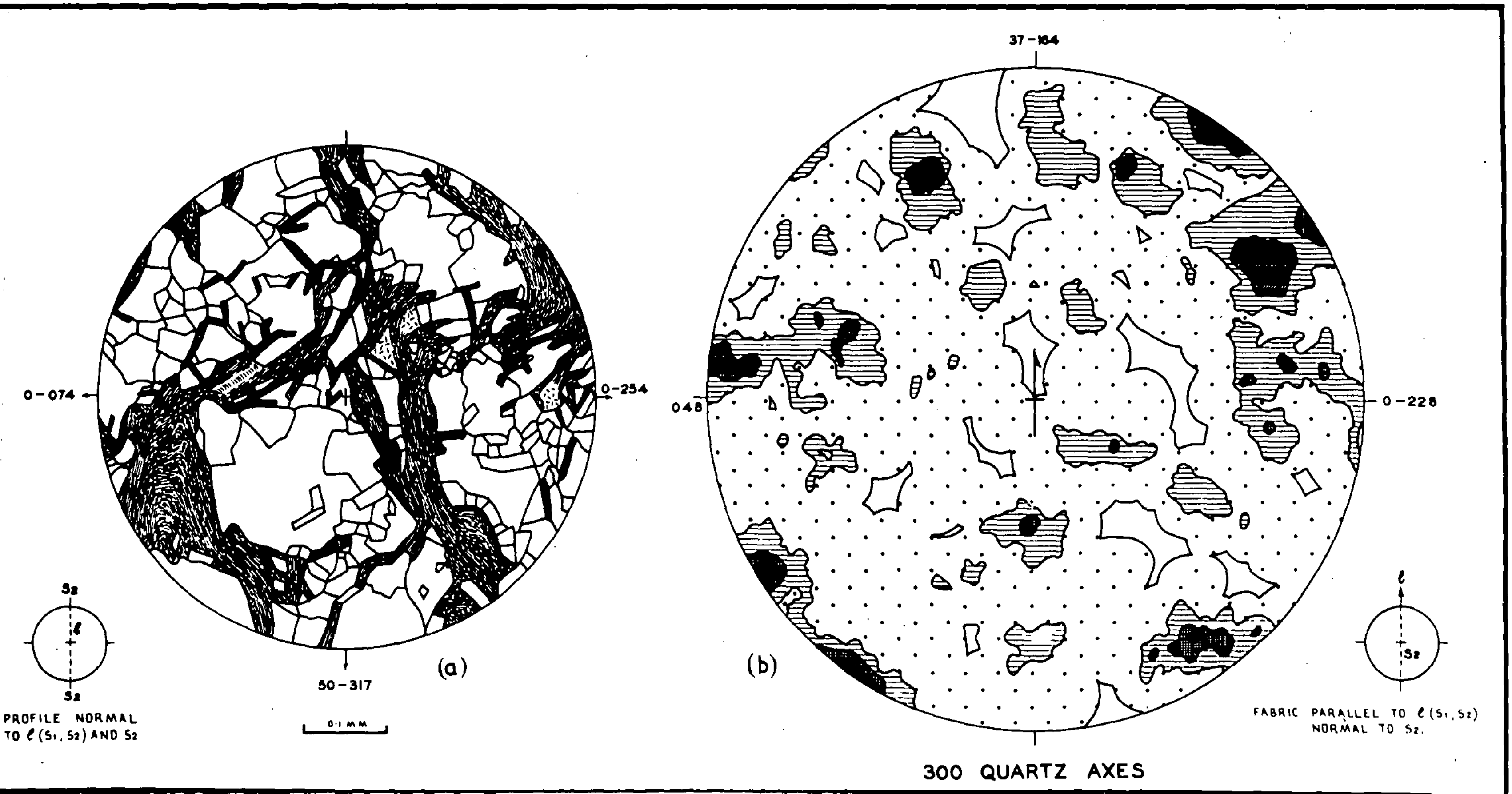
have been added together to give figure 63b. Although there is a tendency for a mortar texture (figure 63a) it is not sufficiently well-defined to justify separating the grains into different classes. A partial small or great-circle distribution of optic axes about the direction of S1 x S2, expected from the texture shown in figure 63a, is not developed. Instead there is a tendency for the plane normal to both S1 x S2 and S2 to be a monoclinic symmetry plane (figure 63b - note that figures 63a and 63b have different orientations with respect to the rock).

Spry (1961, pers. comm.) has described the grain fabric of a number of tectons. There is a mica foliation parallel to S2. The quartz has a mosaic texture with large, undulose quartz forming a girdle normal to the L-axis with either monoclinic or approximately orthorhombic, symmetry. The small, clear grains are dimensionally elongated and have either monocline or triclinic symmetry in different specimens.

In some specimens the partial fabrics of large and small grains is orthorhombic and monoclinic, respectively. In other specimens the respective symmetries are monoclinic and triclinic. However, work since 1961 has indicated (A.E. Spry, pers. comm.) that the internal fabric of the tectons is complex with domains of different types of fabric occurring in different portions of the tecton interior.

In earlier work on conglomerates in tectonites

Figure 63



Texture (a) and quartz grain fabric (b) in schist forming the conglomerate matrix, area 2, Goat Island

(Oftedahl, 1948 and Flinn, 1956, in particular) it has been assumed that the tectons are passively deformed bodies of original closed form (pebbles) and that the final shape is a measure of strain. At Goat Island the "modal tecton" is an ellipsoid with symmetry planes parallel to those of other elements of the fabric. The semi-axes **l**, **m**, **n** are in the ratio 4:2:1 which would imply an extension in the L direction (parallel to the B(1,2) axes) of 100 percent. This approach is not adopted here for the following reason.

It is possible that the Goat Island Conglomerate contains tectons of diverse origins. Some may be original pebbles, but many are only parts of originally larger bodies of quartzite. The "nested tectons" of figure 57j appear to have been "peeled-off" a single body as concavo-convex tectons "nested" around an ellipsoid core. There is every transition between the "boudinaged" tectons of figure 57q and the "tadpoled" tectons of figure 57p. Many large bodies appear to have been "necked-down" and pulled-apart to form smaller bodies. In one area of Goat Island (area 17 of figure 55) there are boudinaged tectons up to four feet long and only inches wide, as shown in figure 57q, which appear to be boudinaged sheets or cylinders rather than spheres. Whether all the tectons were formed by disruption of original pebbles or not, the fact that there has been such disruption renders invalid any computations of strain which

Plate 25

D(1,2) folds with transposed lithological layering (S1).

Area 3, Goat Island.

Hammer two feet long. Looking south.

assume constant volume.

The tectons may be considered more accurately, not as "strain ellipsoids" but as "tectonic fish" with a shape controlled by the flowage of the enclosing matrix. The shape yields information on the symmetry of deformation, but no information of the amount.

In preceding discussion the movement picture has been regarded as orthorhombic with axial tendencies.

The tectons may be thought of as an array of orthorhombic domains. The domains themselves are, however, arranged in a girdle about the B(1,2) axial direction, that is, there is a radial perturbation of domains. This indicates that deformation was heterogenoous, the interior of the tectons being deformed differently to the matrix between tectons. The "polished skin" or micaceous coating on the tectons is consistent with slippage at domain boundaries. The "splitting-off" (figure 57j), pulling-apart (figures 57l, p, qu) and "fraying" (figure 57e, f, p) of tectons indicates that the tectons have not been coherent units during deformation but have been "milled-down". Possibly the tectons have been deformed towards an ultimate shape, but those of certain orientations or shapes have also been split up into pieces approximating the ultimate form. The "ultimate form" is the form which is stable in the flowing matrix. The deformation of the tectons is therefore regarded as a "stream-lining" to fit the conditions of rock flow rather than a deformation representative of the whole rock body.

The shape of the tectons, if a response to rock flow, should reflect the characteristics of the flow. It has been shown that the one element of shape which is exceptionally narrowly defined and is largely independent of shape class or tecton size, is the eccentricity in the LN plane. The LN plane is therefore the principal deformation plane.

Where the LN planes of groups of tectons are oriented parallel to each other, deformation was orthorhombic. Where they are perturbated, deformation was of axial symmetry. The conglomerate was deformed in the B(1,2) phase by a "three-dimensional" flow with the principal component of strain being an extension parallel to the B(1,2) axes.

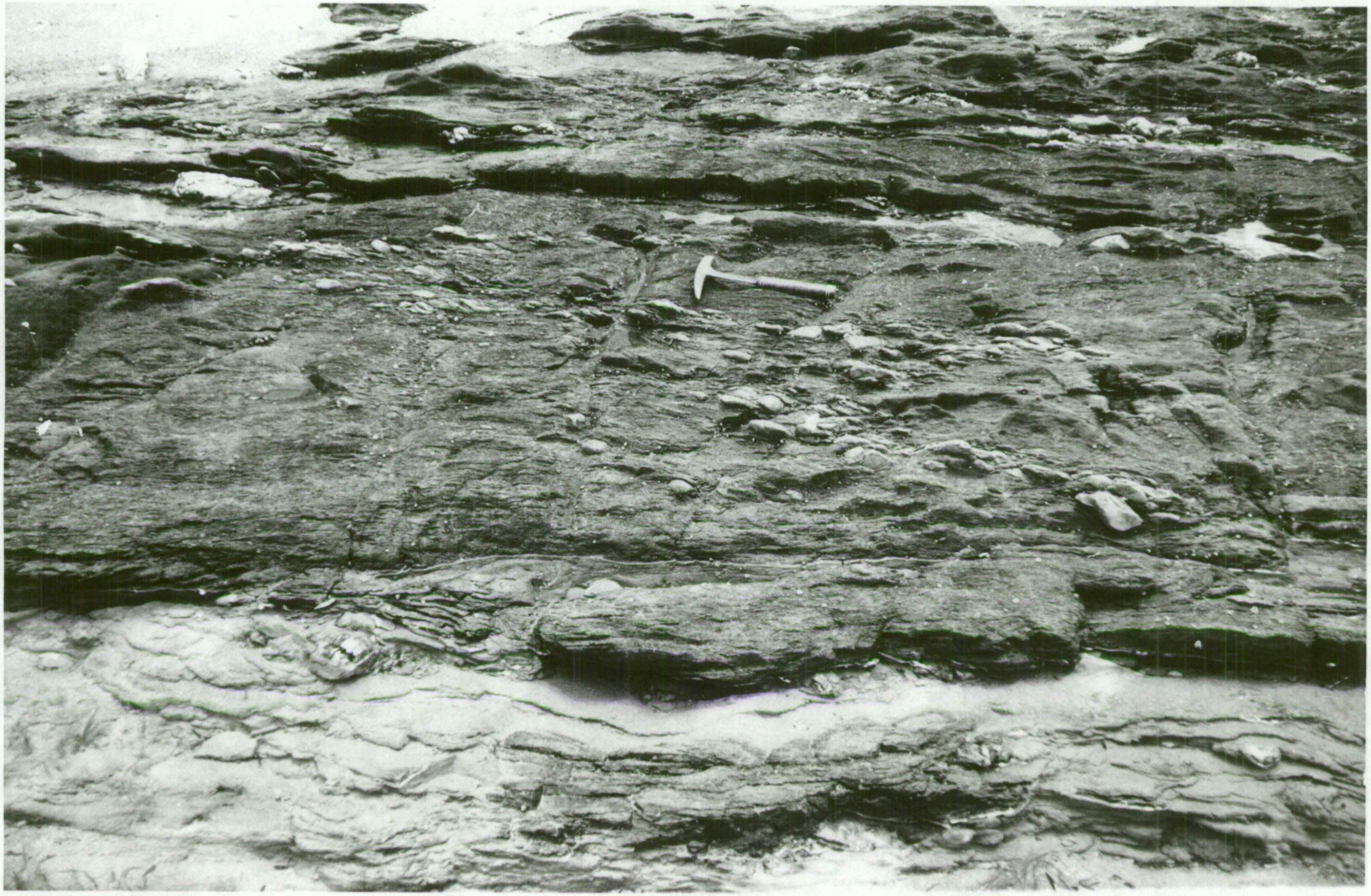
The deductions made for subarea 2, on Goat Island, are generally applicable to the rocks in adjacent areas.

In many areas (subareas 3, 5-9, 13-14, and 15-17 of figure 55) the lithological layering S1 is completely transposed, as illustrated in plate 25. In these areas the foliation S1 is transposed into parallelism with S2 and the LM planes of tectons are aligned parallel to S2. The overall symmetry of the fabric is orthorhombic.

Plate [illegible]

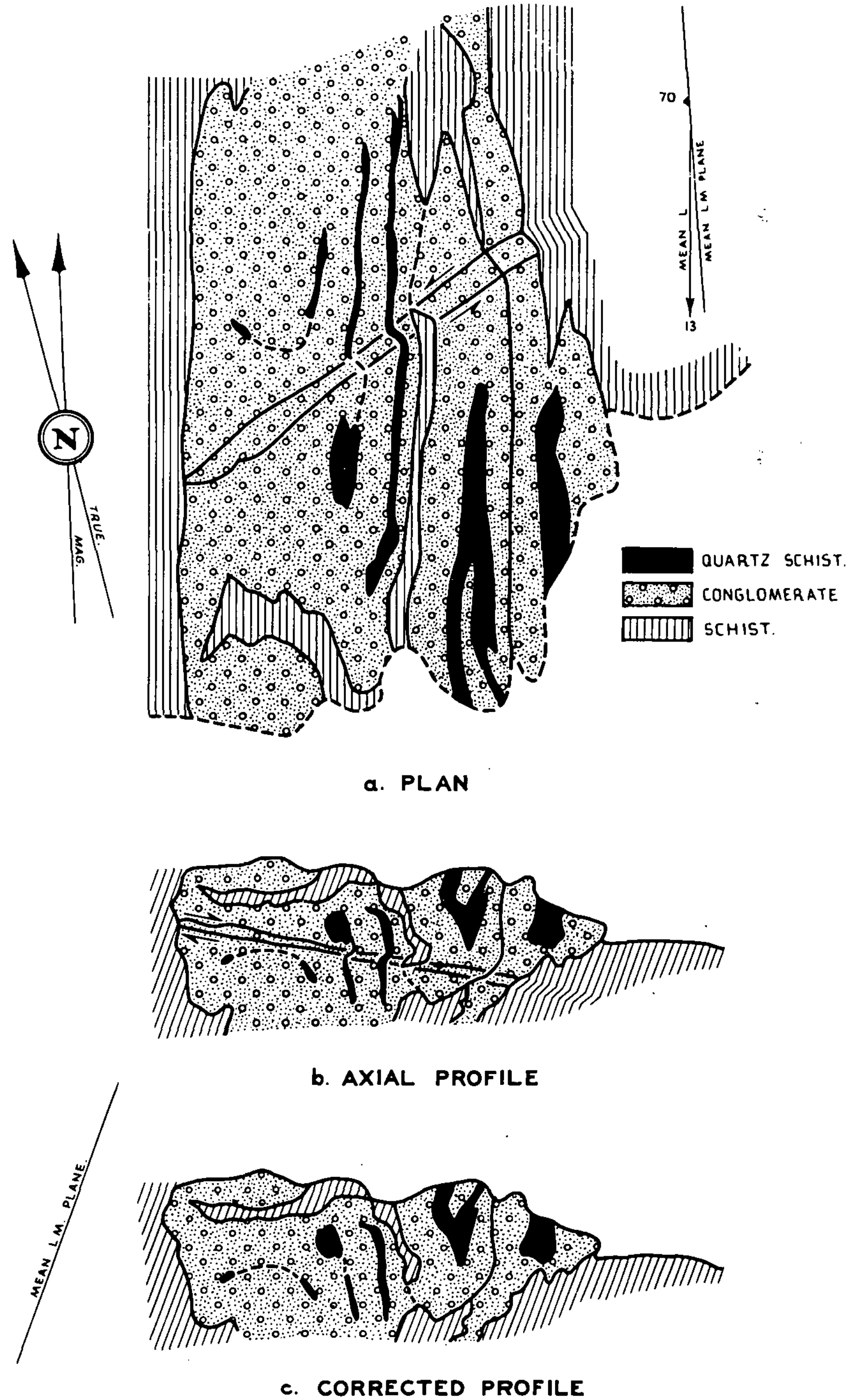
Pebble-band? marking unconformity (?) in schist, area 19, [illegible] Island.

Looking south-west. Hammer one foot long.



Profiles of some typical folds are shown in figures 64 and 65. Fold hinges are preserved but many limbs are cut off. The limbs are disrupted when the attenuated thickness decreases to a size comparable to that of the tectons, that is, at widths between six and twelve inches. Because of this disruption, not all isolated lithological strips are fold closures. There is unlikely to be any more major closures than those shown in figure 67b. The deformation of S1 was not a tight folding followed by transposition, but was transposition following fairly open folding with few minor folds.

The three-dimensional deformation appears to be reflected on the small-scale maps. In figure 69 there is a convergence and divergence of modal S2 (and LM) in plan which is not to be explained in terms of superposed deformations. Figures 67 and 64 show that the traces of the axial surfaces of folds are not strictly parallel to the trace of S2. The traces of the axial planes are "stopped" across S2. (See particularly the antiform of figure 64c). This may be interpreted as a variation in the amount of slip at different parts of a single S2 foliation plane (assuming that continuous foliation planes exist). The slip was not constant at all points in the foliation plane, but varied along the strike-length of the foliation. In the area of figure 65 there is a tendency for S2 to converge downwards in synforms and



PROFILES-PART OF AREA 14 – GOAT IS.

Figure 64

upwards in antiforms which may be due to variations in depth of the amount of movement on S2.

There are indications, therefore, of "contemporaneous cross-folding" with the amount of movement on S2 varying along the strike- and dip-lengths of S2. The variations reflect variations in the relative magnitudes of the principal components of strain.

The variations in the style of the B(1,2) folds may be explained as follows. Where the principal movement plane is the horizontal plane, the principal deformation of S1 is in a plane parallel to S1 and is not observed. The large, open folds of S1 are a consequence of the subsidiary component of strain. Where the subsidiary component is relatively large, S1 is tightly folded and attenuated limbs become disrupted when reduced to thicknesses comparable to tecton diameter. In the first case the ratio of minor (vertical) to major (horizontal north-south), components of strain is small, that is, the ratio of the minor to the intermediate component is large, and the movement picture has a tendency to axial symmetry. In the second case the ratio of the minor to the major component of strain is large and the movement picture is orthorhombic.

With regard to the tectons, their history may only be deduced from comparison with the undeformed rock type or from the history of the grain fabric. The conglomerate

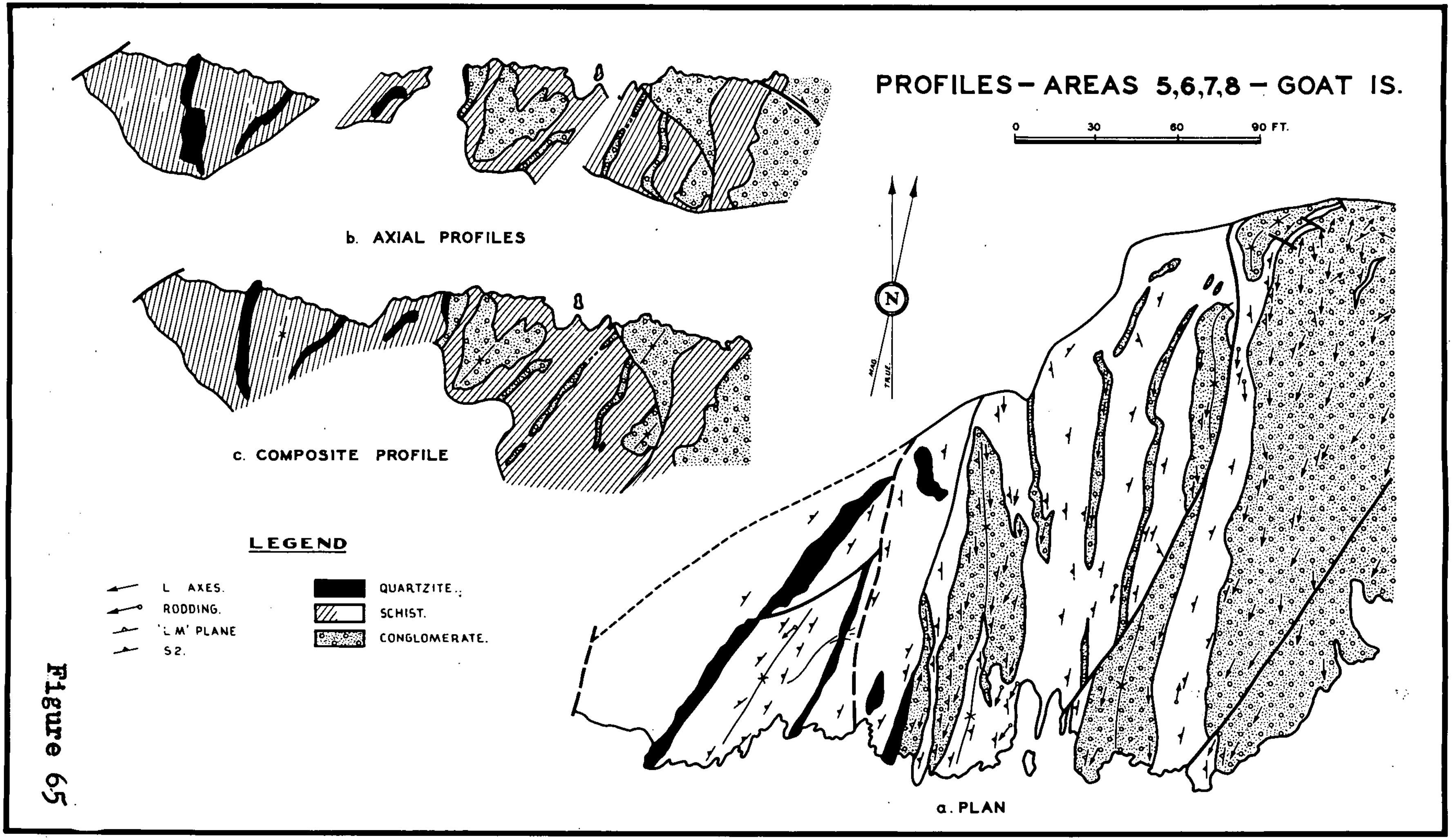

PROFILES – AREAS 5,6,7,8 – GOAT IS.
0 30 60 90 FT.
b. AXIAL PROFILES
c. COMPOSITE PROFILE
LEGEND
L AXES.
RODDING.
'L M' PLANE
S2.
QUARTZITE.
SCHIST.
CONGLOMERATE.
MAG.
TRUE.
N
a. PLAN

Figure 65

could have been formed by deformation of an original pebble bed, by boudinage of mullions, by chocolate-tablet boudinage of sheets, or by disruption into slivers of massive rock, or by any of these mechanical processes in combination. All these processes are known to have occurred in the metamorphosed Precambrian rocks in various parts of Tasmania. However, at Goat Island it is possible to apply some restrictions to the number of possible processes.

The tectons have a shape which is, for the mode, an ellipsoid. The axes of the modal ellipsoid are in the ratio 4:2:1. The significance of this ratio is that the quantity $\underline{ln} = \underline{m}^2$, or $\underline{m:r} = 1$ where $r^3 = \underline{lmn}$.

The principal deformation plane of each tecton was the plane LN as is indicated the low dispersion of eccentricities in this plane. The deformation may be thought of as having shaped the tectons so that the eccentricity in LN was of a uniform value. That is, the ratio $\underline{l:n} = 4:1$ is a direct consequence of the deformation. In order that the observed shape be formed, it is necessary to introduce an extra, independent boundary condition. For deformed spheres this condition is that volume be conserved and the area of LN invariant, during deformation.

For deformed prolate ellipsoids, the additional boundary condition is that the volume and the area of LN be conserved, as found by Oftedahl (1948). It is possible to devise boundary conditions for producing the tectons from any original shape. If the original shape was "open", such as a mullion (a cylinder of elliptical cross-section), the required boundary condition is an expression of the ratio of inter-nodal length of the boudins to the diameter of the original mullions.

From symmetry considerations, the final orthorhombic shape implies an initial spherical or orthorhombic shape of the tectons. The original shape could have been, if suitably oriented, spheres, ellipsoids, mullions, or tightly folded layers.

East of Goat Island

At Goat Island it is likely that S1 was originally horizontal, and that the principal axes of strain in the B2 phase were geographically oriented. However, in the general case there will be non-coincidence of S1 and a principal plane of B2 deformation, with a resultant triclinic fabric. This could occur, for example, with non-coincidence of the axes of B(1,2) folds with the L axes of tectons, or axes of quartz rods. A reconnaissance has been made to the east of Goat Island, in search of such a macroscopic fabric. A lithological map of one such area, about 1500 feet east of Goat Island, is shown in figure 66, together with geographically oriented diagrams of the quartz fabric in the quartzite.

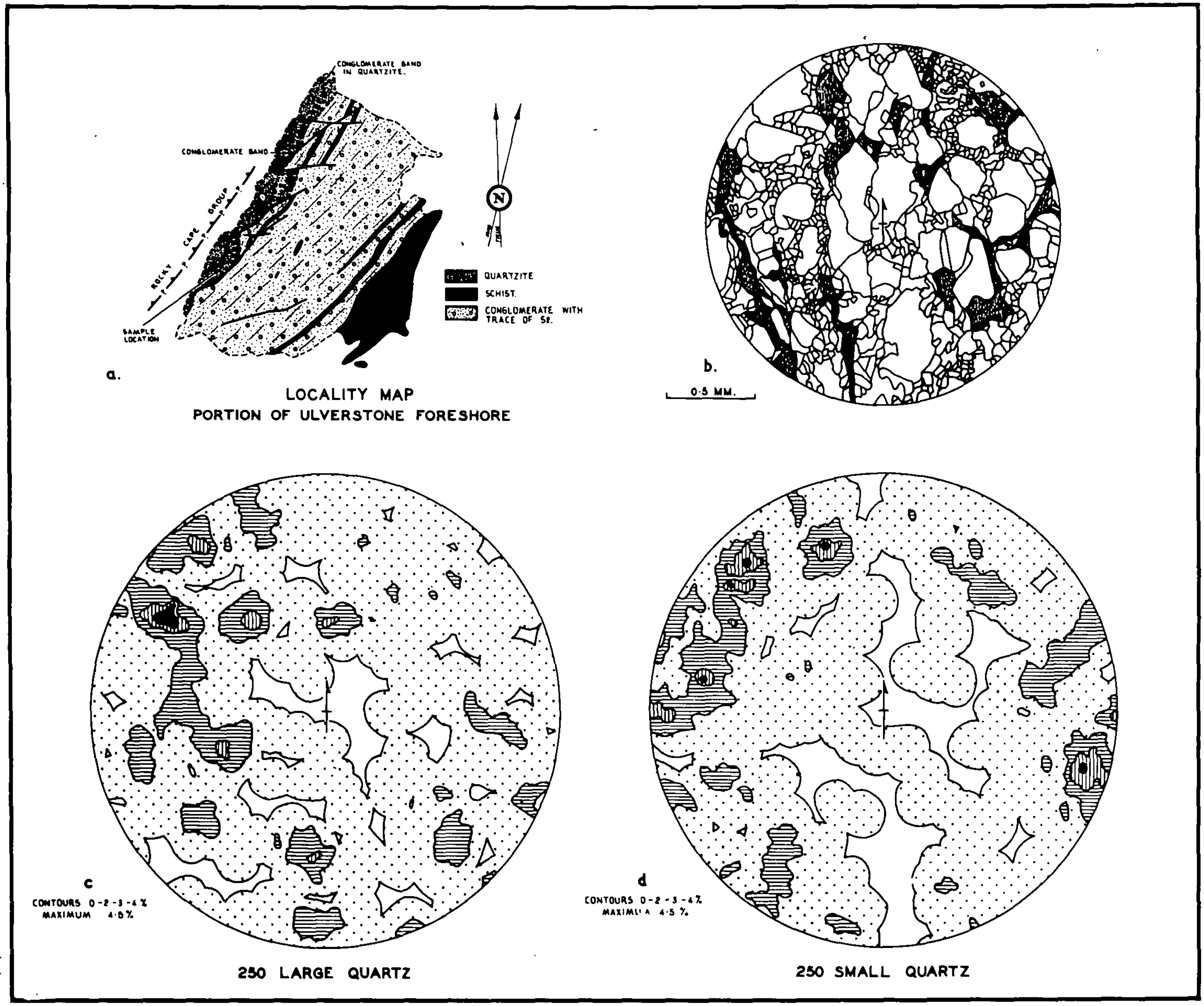


Figure 66

Grain fabric of a quartzite from east of Goat Island.

S2 in the interbanded schist, and the modal L plane (the latter poorly defined) dips 86W026, the modal L axis pitching close to twenty degrees north in L. This orientation is preserved throughout the conglomerate. The conglomerate is overlain by quartzite, the nature of the contact being uncertain, but probably a thrust. The presence of a band of conglomerate in the quartzite shows however, that the two lithologies are closely related. The quartzite contains tight isoclinal folds with axes plunging 55-185 with an axial plane foliation dipping 85E026, with cognate lineations. The quartzite has a mortar texture, with triclinic fabrics for each grain class. The small, clear grains, presumably younger, have a tendency to monoclinic symmetry which is absent in the large grains. The texture is very similar to that described by Spry (1961) for the tectons of Goat Island. A colour banding in the schist matrix of the conglomerate describes folds plunging steeply south, despite the fact that the L-axes of the tectons throughout the folds, plunge gently north. If the layering in the quartzite, and colour banding in the schist, are both S1, the fabric of this outcrop is triclinic, and as expected from the movement picture obtained at Goat Island.

The textural similarities between this quartzite, the schist from subarea 2, and the tectons described by Spry,

Structural-element map, Goat Island

Figure 67

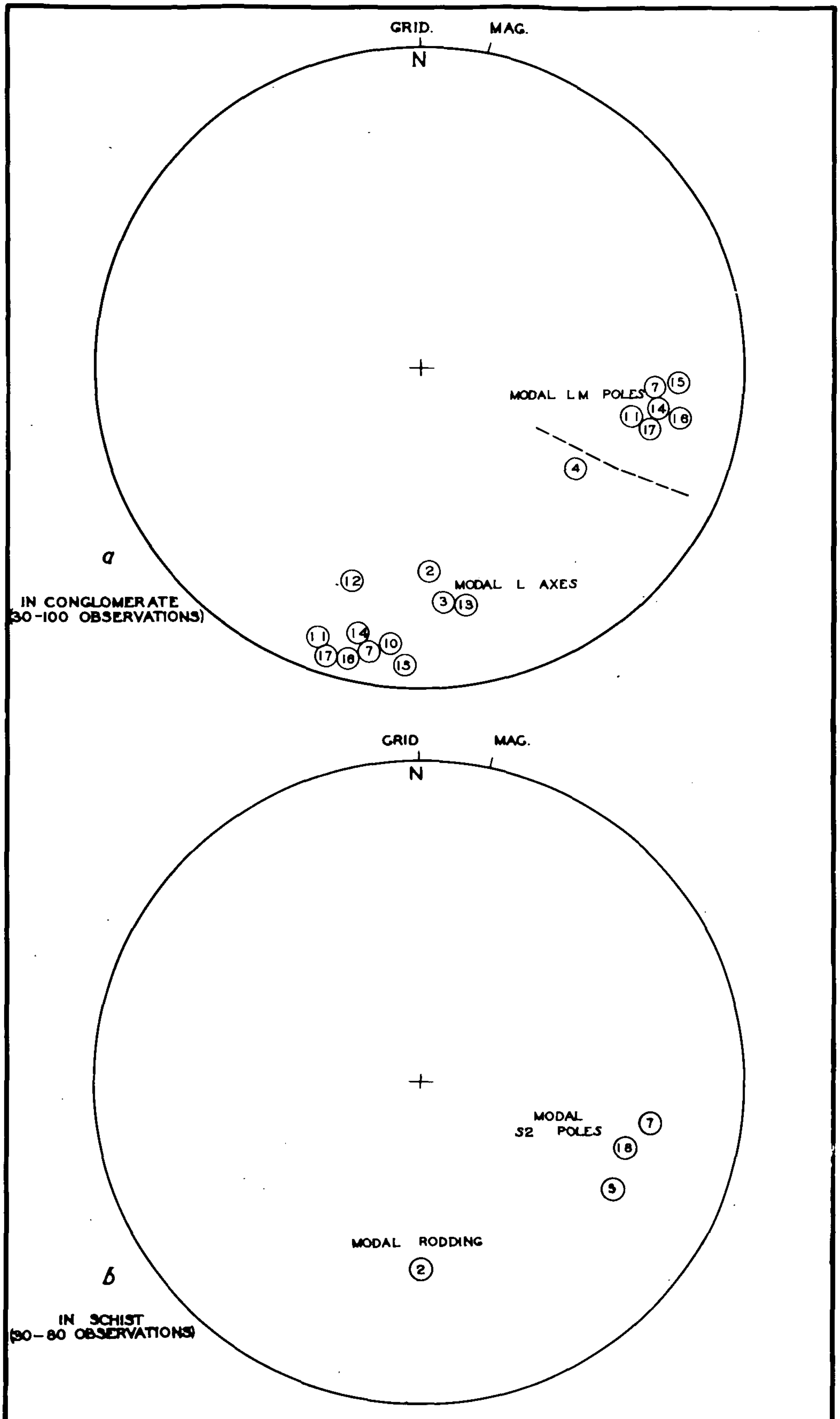
indicates that the three lithologies probably have a similar history. There is, for instance, no justification for postulating unconformable relationships between any of the lithologies.

Late Structures

The Ulverstone Metamorphics at Goat Island record three periods of deformation younger than the formation of the tectons.

Along the footwall on the north side of the fault which strikes north-east and bisects Goat Island there is a narrow zone of wide-spaced crenulation cleavage. The cleavage extends to a distance of about thirty feet from the fault, but at this distance is little more than a close-spaced jointing as in the top left-hand corner of plate 23. The cleavage has a consistent sense of movement (sinistral) on both sides of the large B(1,2) fold of Goat Island and like the fault to which it is related is younger than the B(1,2) folding. The age and affinities of this structure are unknown, but it is possibly of Precambrian age.

There are two periods of post-metamorphic refolding of the foliation S2 at Goat Island which are identified as Tabberabberan (Devonian). The folds formed in these periods are denoted B3 and B4 respectively and are of different orientations and profiles.



SYNOPSIS OF PRECAMBRIAN STRUCTURAL ELEMENTS
GOAT ISLAND

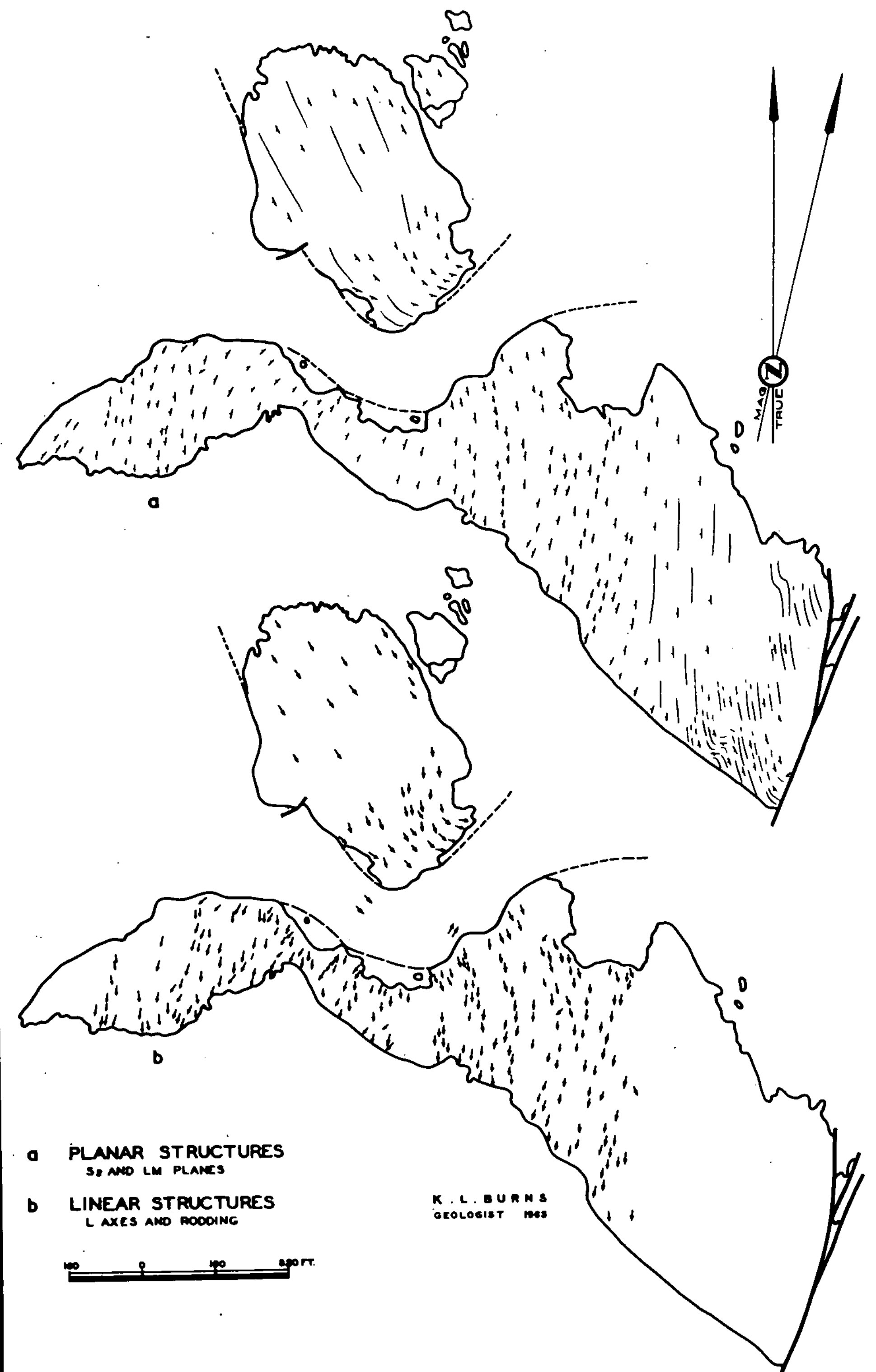
Figure 68

The subareas of figure 55, except for number 19, are areas in which the foliation S2 is uniformly oriented. In figure 68 the modal values of the principal structural elements are plotted, the numbers indicating the subarea. The number of observations represented by each mode ranges between thirty and 100.

Figures 67, 68, and 69 show that there has been only gentle large-scale folding of the Precambrian structures which is of greatest intensity in area 19, adjacent to the Westbank Fault, and in area 4, at the south-east end of Goat Island. Except in these areas, the post-Precambrian structures are minor perturbations such as crenulation and knick-banding.

The B3 folds are open, gentle folds. The largest ones have a wavelength of about fifty feet and are confined to area 19, adjacent to the Westbank Fault. Data from a small portion of area 19 is plotted in figure 70a, where S3 is a widely spaced axial strain-slip cleavage. The projection indicates an axis plunging 16-193 in an axial plane oriented 78W016. The axial trend is significantly divergent from the strike of the Westbank Fault which suggests the anticline nearest the fault is of conical form and rests disharmonically on the fault surface.

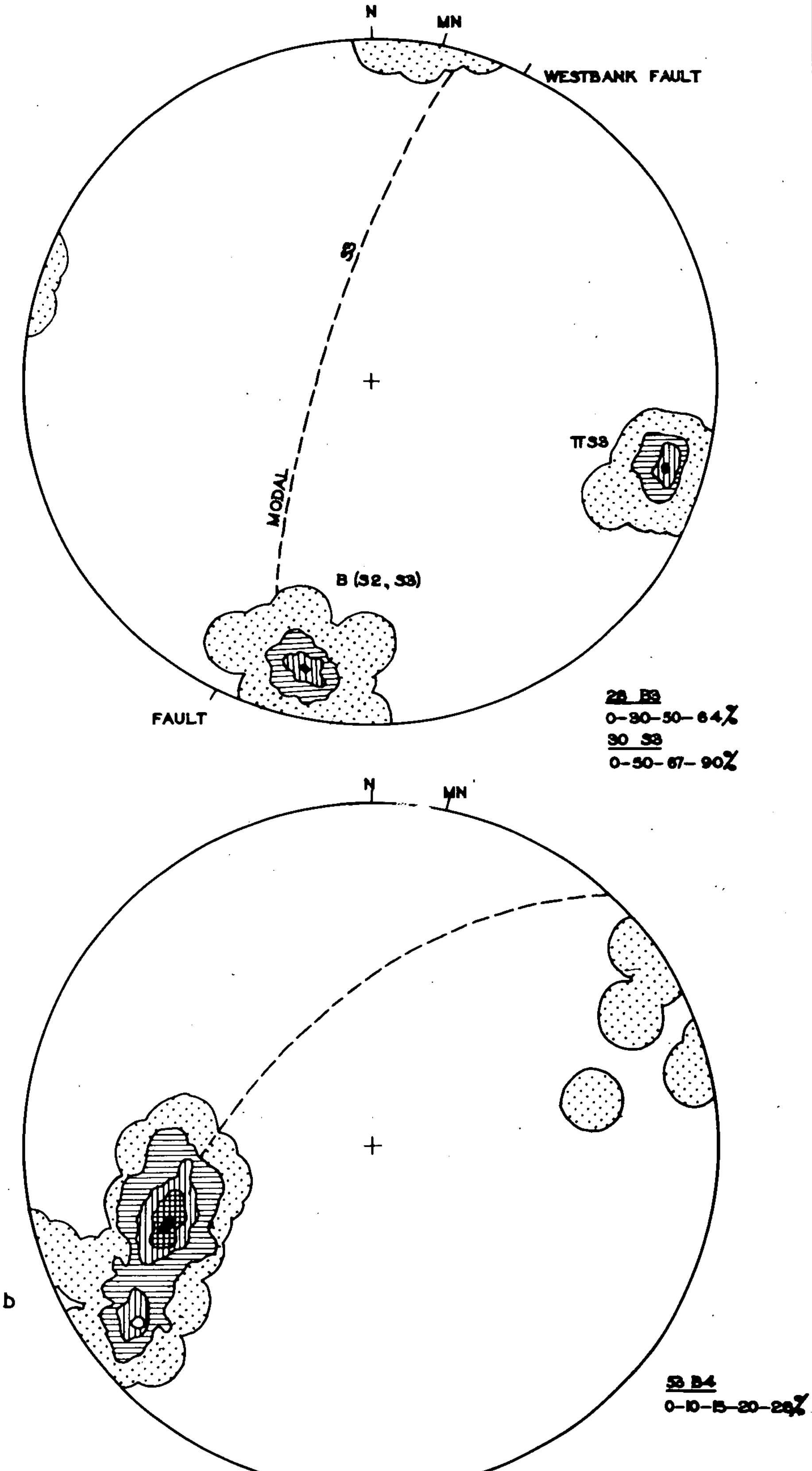
In other areas at Goat Island the B3 folds are minor crenulations of S2 of the schist. The mode at 20-001 in



Structural-element maps of Goat Island. Figure 69 figure 72 is identified as a group of B4 axes. Folds of this generation have not been identified in the main body of the conglomerate. Minor folds in the conglomerate would appear as perturbations of the LM planes, and in view of the Precambrian distribution of LM planes (figure 62c) and the orientation of B3 axes (figure 70a) would be difficult to detect. Large-scale folds, such as in area 19 where a layer of conglomerate is folded in company with enclosing schist, are recognisable.

Structures of the B4 phase of folding have a variable style. There are large-scale folds of the foliation, knick-bands in the conglomerate, and minor crenulations in the schist.

Minor crenulations assigned to the B4 phase are superposed on the B(3) folds of area 19. In figure 70b the axial distribution has modes corresponding to the attitude of S2 (after the B(2,3) folding) in the area sampled. The B3 folds in this area are asymmetrical with gently-dipping western limbs and steeply dipping eastern limbs. The superposed B4 crenulations are well-developed in gently-dipping surfaces, but are either of greatly reduced amplitude or absent in steeply dipping surfaces. A single crenulation may be followed up the flat-lying limb of a minor B3 fold to the hinge, but it may disappear on the eastern limb or be represented by only a very gentle



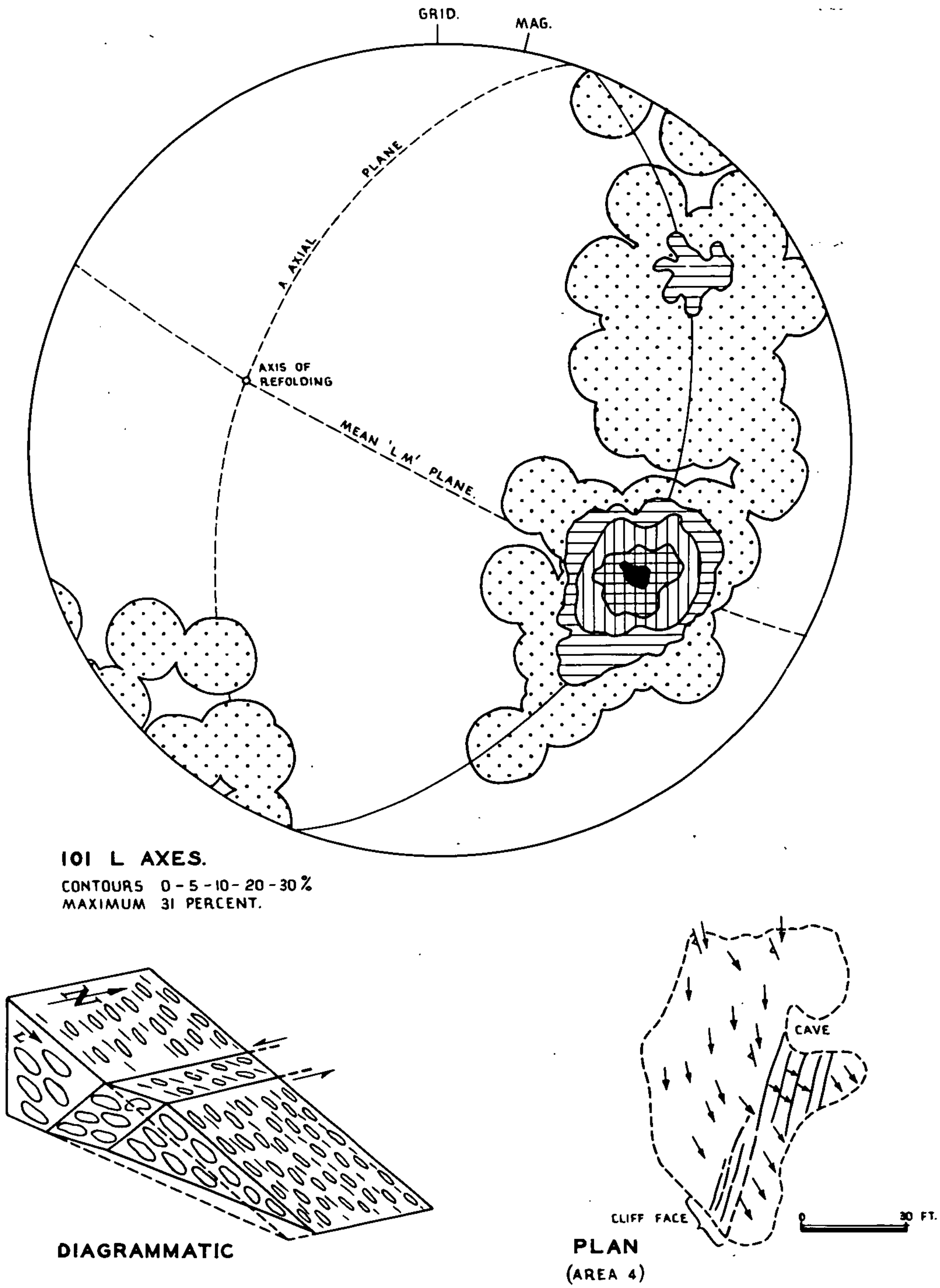
Tabberabberan minor folds, area 19, Goat Island.
Figure 70

undulation. This phenomenon provides evidence of the relative ages of the B3 and B4 folds. Further evidence of age relations is afforded by the displacement of the axial traces of the B3 folds on cross-cutting knick bands of the B4 phase.

The large-scale fold at the south-east end of Goat Island is correlated with the B4 phase. In figure 68 the modal L-axes for areas 2, 3, and 13 are significantly disoriented with respect to modal L-axes for adjacent areas to the south. That is, the Goat Island window appears to be rotated with respect to the marine platform immediately to the south. The hinge of this rotation is located at the south-east end of Goat Island as illustrated by figure 69a.

In figure 71 is plotted a sample of L-axes from this area. As has been discussed, the L-axes are very well oriented in areas of homogeneous Precambrian structure, so they may be utilised to determine distortions of that structure.. In order to use the LM planes, however, it is necessary at each sampling site to measure at least fifty and find the mode of the distribution. The modes from a number of sites may then be used to measure the folds. In this example the scale of the late structure is too small for the LM planes to be determined in that fashion.

In the plot of L-axes, the principal mode at 42-122 is the local modal orientation of L. The subsidiary mode



LATE CROSSFOLD — GOAT ISLAND

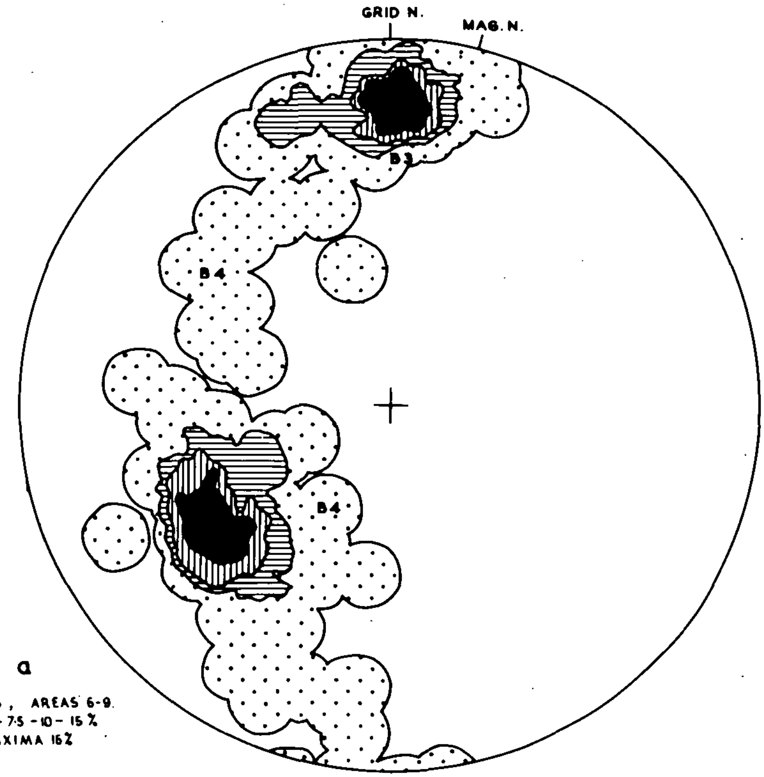
Figure 71

at 25-056 is the orientation that the L-axes tend to have in the knick-bands as illustrated in figure 71b. The bimodal distribution reflects the abrupt "knicking" that occurs in structures of the B4 phase.

This fold is exceptional owing to the coincidence of several factors. The axial plane of the fold is virtually a fault and is oriented normal to both the mean LM plane and the direction of the L-axes in that plane. As a result, the axis of refolding of the LM plane is ninety degrees from the modal L-axes. The axial plane of the fold is 48NW020 and the axis 49-291.

Minor crenulations in the schist of areas 6 to 9 are plotted in figure 72a. The mode at 20-001 is identified as B3 folding, the mode at 43-230 is correlated with the B4 phase. There is a very weak mode near 47-301 which is well-developed in some small areas and which is correlated with the B4 phase.

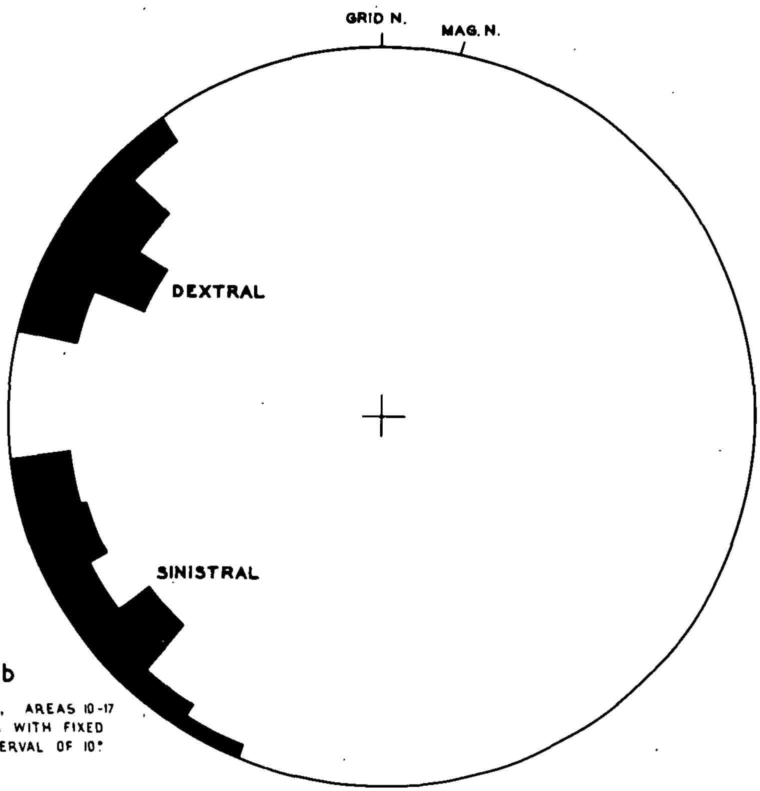
The main body of conglomerate on the coastal marine platform south of Goat Island (areas 10 to 17 of figure 55) is crossed by a number of knick bands similar to that one shown diagrammatically in figure 71. A map of one of these bands is shown in figure 64. The knick bands are non-penetrative structures which run in straight lines across the outcrop, like vertical faults. They may be divided into two classes - knick bands with sinistral displacement,



a

103 AXES, AREAS 6-9.
0 - 5 - 7.5 - 10 - 15 %
MAXIMA 16%

FLEXURAL FOLDS IN SCHIST



b

75 STRIKES, AREAS 10-17
HISTOGRAM WITH FIXED
CLASS INTERVAL OF 10°

KNICK PLANES IN CONGLOMERATE

Areas 7-14, Goat Island

Figure 72

[illegible] conjugate, and kink bands with dextral displacement, which strike northeast. A histogram of the strike of a sample of kink bands is shown in Figure 77c. It is possible that the kink bands are of several generations and that the dihedral angle between planes was different in each generation. The kink bands vary along their length. They have a wide middle portion with large displacement, and toward the ends the bands narrow and displacement decreases. Some diagrams of lithological lamination as shown in Figure 77e (kink-band area). They cut straight across the conglomerate and the axis of folding at any point depends on the initial orientation of the folded structure. The fold of Figure 72 may be regarded as a group of kink bands.

In the schist of area (C-2) the axes of [illegible] folds are oriented [illegible] and [illegible] (Figure 77a). The strikes of kink bands in adjacent conglomerate are 297 and 327 (Figure 77b). If these measurements are combined, they define kink bands oriented [illegible]297 and [illegible]327 with their line of mutual intersection being within four degrees of vertical. These orientations for the kink bands agree with field observations. The kink bands form a conjugate system with orthorhombic symmetry, the symmetry planes being [illegible], [illegible], and [illegible]. The divergent axes of [illegible] crenulations in schist bands within the conglomerate appear to result from superposition of the knick bands on the S2 foliation in the schist with the crenulations being formed in kinematically passive schist at the intersection of the knick bands with S2.

This pattern of folding contrasts with the examples of Johnson (1956) in which the foliation is kinematically active and the line of intersection of sets of axial planes lies in the foliation and the folds have axes parallel to this line. The pattern resembles that described by Hobbs (1962) in which the axes of superposed folds form a pencil which has an axis at an angle to the foliation, and the term "joint-drags" or "knick-drags" is perhaps more appropriate than "conjugate" folding.

CHAPTER 10

STRUCTURES IN THE FORTH METAMORPHICS

CHAPTER 10

Structures in the Forth Metamorphics

Introduction

The rocks of the Forth Metamorphics are garnet-mica schists, quartzites and amphibolites, which have been regionally metamorphosed to garnet grade. The possibility of higher-grade rocks is suggested by reports of Petterd (1893, 1896, 1910) of kyanite collected by Gould in 1873 at the Clayton River. However, rocks of this grade cannot be found and Petterd's descriptions suggest the possibility that Gould acquired the specimens of kyanite from the widely-travelled prospector, "Philosopher" Smith, who resided at the Clayton River.

The Forth Metamorphics abuts against the Ulverstone Metamorphics in the vicinity of Abbotsham and Spalford. The boundary between the two associations is defined arbitrarily at the contact between garnet-biotite-muscovite schist and chlorite-muscovite schist. This boundary is a major lithological boundary in that the Forth Metamorphics so defined is an assemblage containing amphibolites but no conglomerates and the Ulverstone Metamorphics contains conglomerates but no amphibolites. The boundary is parallel to the foliation S2 which is the dominant S-surface in the two associations.

Rocks of the Forth Metamorphics contain a number of foliations, defined by compositional layering, dimensional orientation of mica or elongated quartz or amphibole, and by optical orientation of quartz. The dominant S-surface is the schistosity and transposition foliation S2. Earlier S-surfaces are preserved as relicts in detached fold cores; later S-surfaces are minor perturbations of S2.

The deformative and metamorphic episode in which S2 was formed is Precambrian in age as is shown by the structural and metamorphic hiatus at the contact between Forth Metamorphics and Palaeozoic rocks on Porcupine Hill. S2 describes sweeping curves in plan which outline major antiforms at Spalford and near Forthside Hill. The Forthside Antiform continues upwards into Ordovician rocks and is therefore a Palaeozoic structure. There has been two identifiable periods of post-metamorphic folding in the Forth Metamorphics which are probably both Tabberabberan.

<u>Structures in Schist</u>

At the western margin of the Forth Metamorphics, near Abbotsham, the schist has a compositional quartz-muscovite layering which is denoted S1. In the field a dark banding is visible which describes isoclinal folds about S1. In thin section the dark layering is due to layers rich in iron ore, which may represent primary compositional layers, and S1 is a penetrative schistosity which is near-horizontal. The regionally-extensive foliation, S2, is an axial structure to open, upright, symmetrical folds in S1 of six inches wave-length, and is a wide-spaced crenulation cleavage with foliae marked by orientated grains of syntectonic biotite. The compound fold form is of the type M on Σ of Ramsay (1962, figure 13).

One mile east of Abbotsham, in the Clayton River, S2 is closely spaced and S1 may only be identified in thin section. Some outcrops are strongly "pencilled" with the lineation S1 x S2 the only macroscopic structure. The pencils are due to rolled-up cylinders of the mica foliation S1.

On the Forth River S1 is completely obliterated mesoscopically. Recrystallisation of coarse muscovite and biotite parallel to S2 has developed a coarse, foliated schist. S1 is visible in thin section as occasional detached cores of isoclinal folds, and is usually a mica foliation but is sometimes a quartz-mica compositional layering.

There are hazards in identifying the latest, macroscopically-dominant, foliation as S2 everywhere. However, the assumption is justified by the resultant continuity of S2 so derived, as in figures 73A and 76.

In the present work, all the planar structures earlier than S2 are grouped together and collectively denoted S1. In areas where sub-classes of S1 may be identified, as in the quartzites of figure 74, the nomenclature Sa, Sb, Sc, is used. In the schist belts, foliations of these subclasses occur but only their interactions with S2 have been observed, not their interactions with each other.

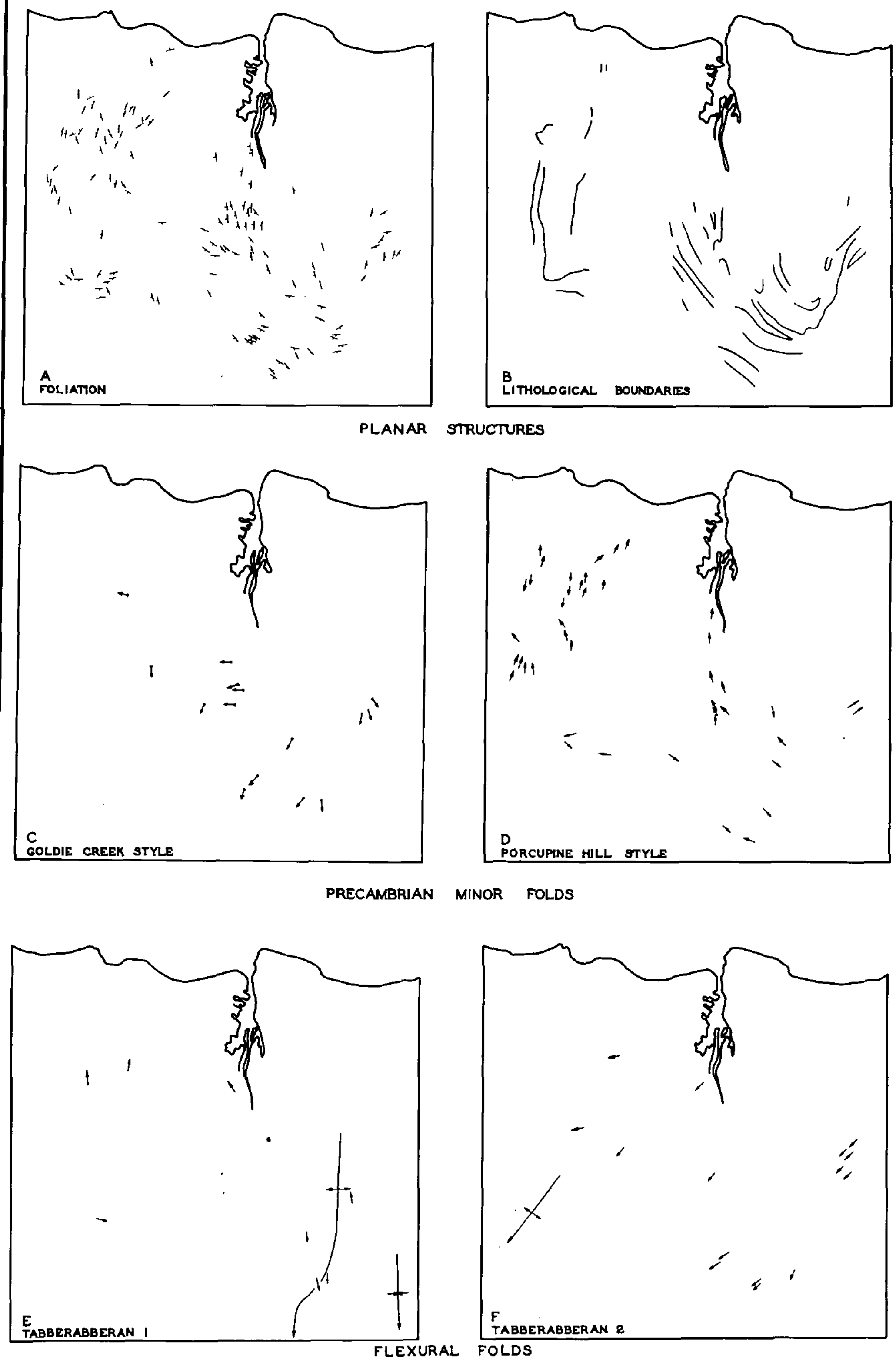
Where foliations of the S1 group are preserved as continuous layers, B(1, 2) folds are formed. At the mouth of Goldie Creek there is a compositional foliation consisting of interlayered quartzite and schist. The compositional foliation is folded into long-limbed isoclinal folds with axial planes parallel to S2, and fold axes which have a steep pitch - near ninety degrees - in S2. The limbs are attenuated to half their crestal thickness and in some cases the quartzite layers break up into bands of quartz augens in the schist.

In an adjacent outcrop about 200 yards south of the mouth of Goldie Creek, there is a belt of greenschist interlayered with the schist. The greenschist has a chlorite-actinolite compositional layering which is folded with the same style and orientation as the folds in the schist. This fold style and orientation is distinctive, and is termed "Goldie Creek Style". At Goldie Creek, the

Goldie Creek style is represented by isoclinal B(1, 2) folds of steep axial plunge, where S1 is a compositional layering, possibly bedding, in schist and is a metamorphic banding in amphibolite.

North-west of Goldie Creek, the belt of granoblastic amphibolite on the western side of the Forth River has a garnet-hornblende compositional layering, and contains layers of secretion quartz. Secretion quartz veins are also common in the schists on the eastern side of the Forthside Antiform. The veins are folded into disjunctive folds - long-limbed isoclinal folds with S2 as axial surface, with the veins pulled-apart and disrupted into strings of parallelopipeds. In every observed example, the axes of these folds plunges within twenty degrees of the down-dip direction of S2. These folds are therefore grouped with the Goldie Creek Style.

Folds of the "Goldie Creek Style" are abundant in certain outcrops, and their median orientation in each outcrop is shown in figure 73c. They are confined to belts of schist and amphibolite and the manner of their interaction with folds of the "Porcupine Hill Style", which characterise the quartzites, is unknown.



STRUCTURAL ELEMENTS - FORTH METAMORPHICS
Figure 73

Structures in quartzite

The quartzites contain several foliations. There is a compositional quartz-muscovite foliation(Sa of figure 74)in some outcrops which consists of alternating layers from one-quarter to one inch thick.

There is a foliation(Sc of figure 74)due to dimensional elongation of quartz, the quartz grains being flattened lenses or augens. This foliation gives a "fibrous" appearance to otherwise massive quartzites and is very prominent on weathered surfaces of "quartz-schist" (micaceous quartzite). In vitreous (mica-free) quartzites the foliation is sometimes visible as a "grain" or linear fracture pattern on freshly broken surfaces.

Some quartzites contain a second mica foliation(Sb of figure 74)which is marked by alignment of muscovite grains. This foliation outcrops on compositional surfaces (Sa) as mica "trails", or glossy lines on the surfaces due to concentration of muscovite at the foliation trace.

The compositional foliation Sa is found folded in places with the mica foliation Sb parallel to the axial planes of the folds, so that Sb is younger than Sa. However, in most outcrops the three foliations are sub-parallel to each other and to S2 of the adjacent schists.

Linear structures in the quartzite consist of minor folds of the type B(Sa, Sb), and lineations formed by the intersection of foliations. There is no small-scale puckering or crenulation of any foliation.

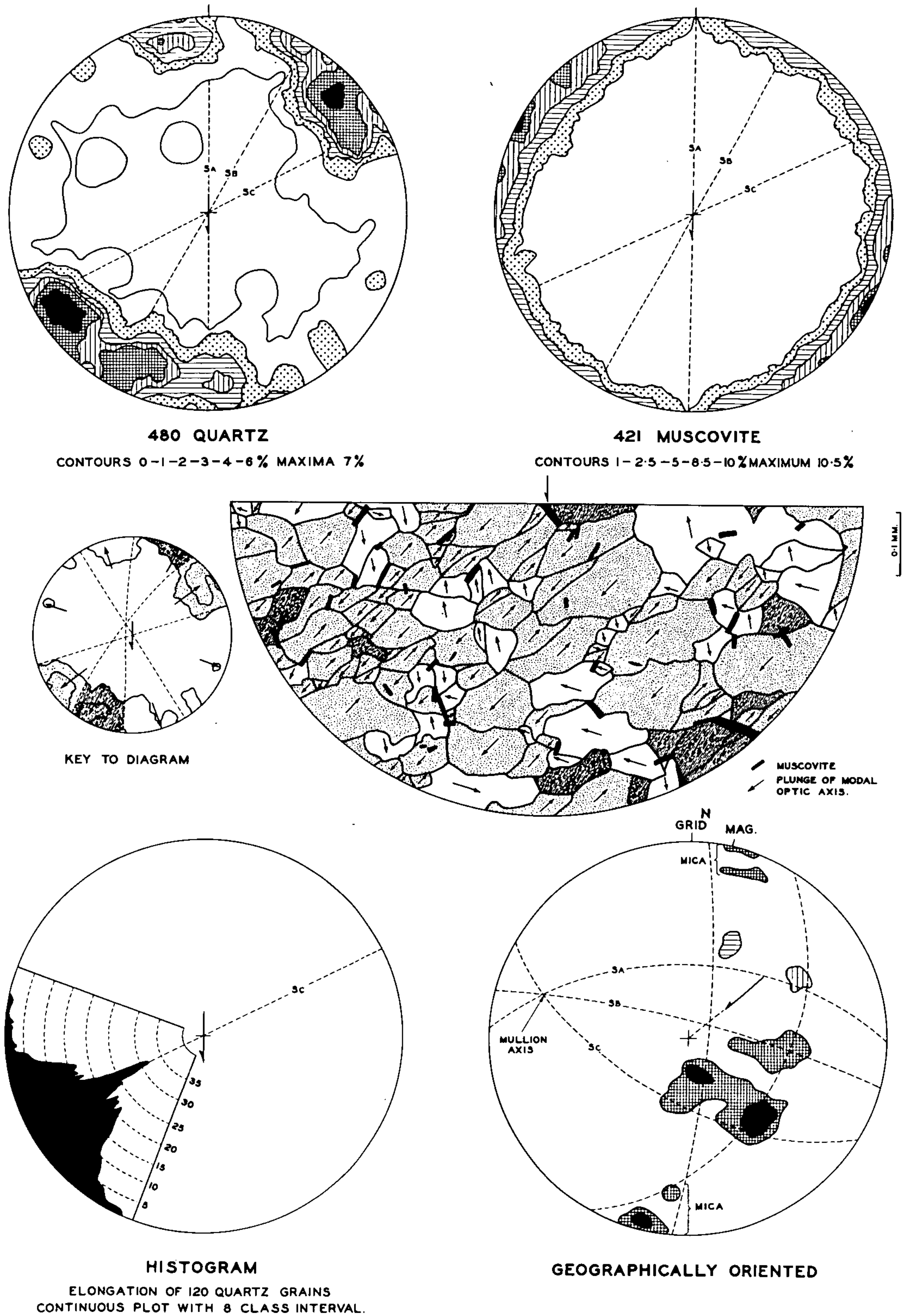
No outcrops occur in which the lineations are of variable plunge and each body of quartzite is superficially homogeneous in this respect. For example, at Sayers Hill the quartzite fish nearest the Forth River has a strong mullion structure which pitches between 75 and 85 degrees north in S2 and has no other macroscopic lineations. In comparison, the adjacent quartzite on the eastern side (probably a rooted mass) has a number of minor folds which plunge close to thirty degrees north in the foliation but has no refolded or superposed minor lineations. No outcrop with mesoscopic triclinic fabric could be located.

The predominant minor linear structure in the quartzites is a mullion structure which includes both fold mullions and irregular mullions. At all observed localities, except two, the mullion structure pitches within twenty degrees of horizontal. The exception is the inferred tectonic fish at Sayers Hill and another small body of quartzite half a mile southeast of it. The orientation and style of this mullion structure contrasts markedly with that of the "Goldie Creek Style" lineations, and is termed "Porcupine Hill Style" to facilitate discussion and to emphasise the style contrast.

The grain fabric of a fold mullion from Porcupine

Hill is summarised in figure 74. There is a quartz-mica compositional layering Sa, which is folded. A second mica foliation, Sb, and quartz-elongation foliation, Sc (defined in the histogram) have lines of intersection with Sa which are parallel to each other and to the axis of the mullion at 25-275. The foliation Sc is parallel to S2 in adjacent schists and to the axial surface of (Sa, Sc) folds.

Quartz grains of all optical orientations are undulose, but those with optic axes lying in Sc are dimensionally elongated parallel to Sc and are strongly undulose. The grains are split up into fragments along gently curving fractures sub-parallel to the optic axes. Fairbairn (1949, pp.117-120) suggests that this pattern arises from crystallographic control of orientation. The quartz is split into fracture needles bounded by the rhombohedra r(1011) and z(0111) which lie in the ab plane of the fabric with needle-axes (r:z) parallel to a. The girdle requires rotation about the fabric axis b, here the mullion axis. Hietanen (1938) suggests the orientating mechanism is a late stage prism gliding in grains constrained against external rotation. This ruptural deformation would be responsible for the bifurcated girdle which on this view would be a late feature post-dating the primary orientation. The split



Grain fabric of a mullion from Porcupine Hill

Figure 74

girdle may also be interpreted as due to passive refolding of grains with optic axes having an inherited orientation at a large angle (near eighty degrees) to the mullion axis, as in Weiss (1955).

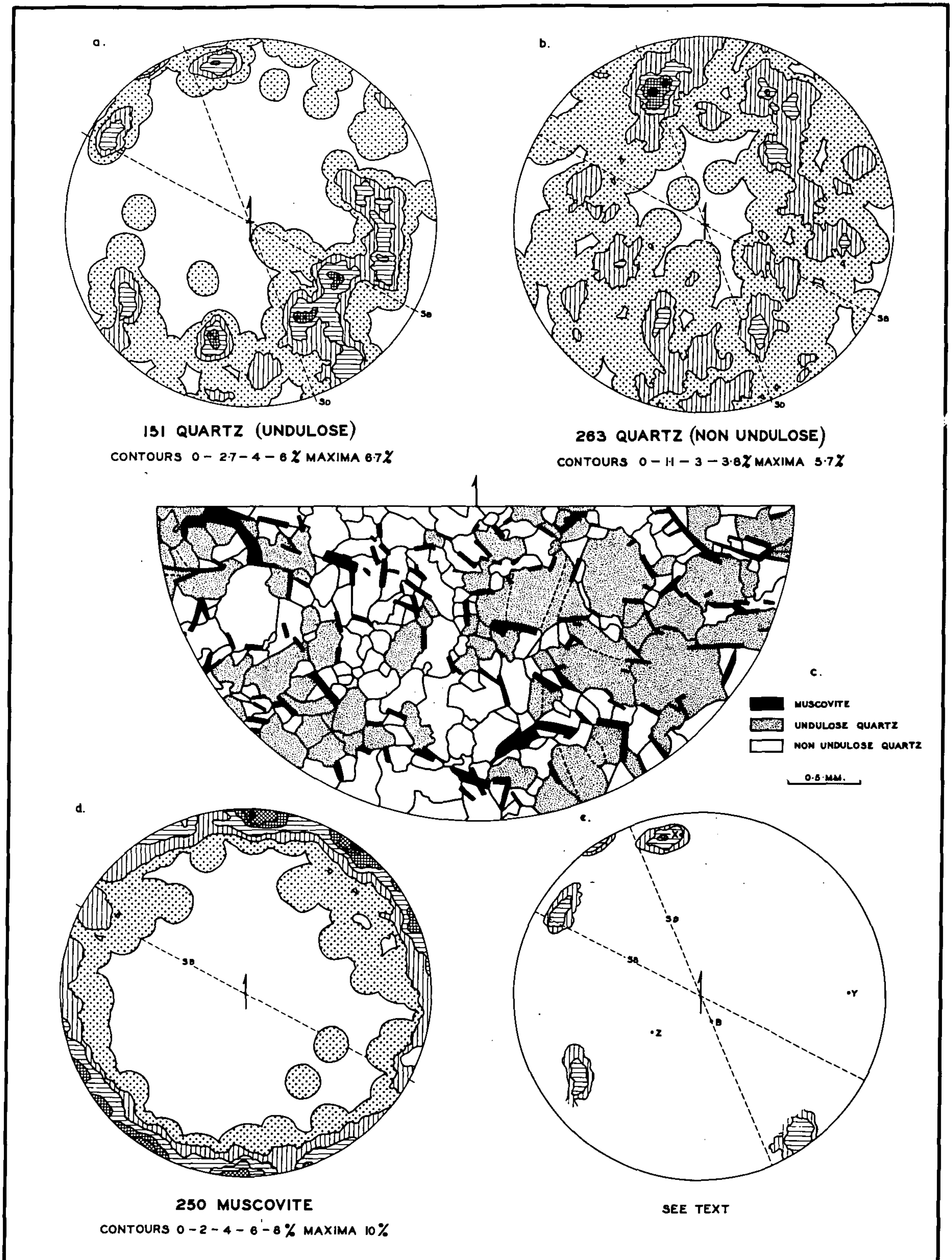
The split girdle is real, as the quartz diagram is the sum of two partial diagrams at right angles which have similar patterns. It is a common feature of metamorphic quartzites in the Tasmanian Precambrian (Spry, pers. comm.). Observations in the field indicate that the foliation Sa is folded and the foliation Sc is superposed so the evolution of the fabric is probably complex and controlled by the probably well-oriented, inherited fabric.

The quartz fabric is triclinic but if the bifurcated girdle is neglected, is monoclinic, as in similar rocks described by Gilluly (1934). As well as having a mode with optic axes lying in Sc, there are quartz maxima in the subsidiary foliations Sa and Sb. It is suggested that the maximum in Sa is mimetic after the inherited foliation Sa which is probably bedding. The maximum in Sb could be mimetic after an inherited foliation such as cross-bedding, or else the foliations Sb and Sc could have been superposed simultaneously.

The quartzite mullion from Sayers Hill (figure 75) is a sample from one of the two places where the "Porcupine Hill Style" lineation has a steep pitch in S2. The outcrop is a lenticular body of quartzite about 400 yards long and no more than fifty feet thick which occurs as an, apparently rootless, pod in schist.

The quartz grains may be divided into two classes, undulose and non-undulose. The undulose grains have optic axes oriented, with respect to the mullion axis, in a pattern similar to the Porcupine Hill rock. (Compare the quartz diagrams of figure 74 and figure 75a). This supports an inference based on field work, that is, that in the Sayers Hill tectonic fish the Porcupine Hill Style lineation has been rotated by bodily movement of the fish. That is, the Sayers Hill mullions were formed in an early deformation phase with sub-horizontal attitude, and were rotated into their present position by rigid rotation with axis of rotation normal to S2.

The non-undulose grains have a different pattern to the undulose grains. There is a large maximum in an inferred foliation Sd (not visible mesoscopically). In figure 75c are shown maxima for undulose quartz which are absent or reduced in intensity in the non-undulose quartz. With reference to the undulose pattern, the non-undulose pattern shows a significant reduction in peripheral maxima with a tendency for grains to be oriented towards the centre of the projection.



Grain fabric of a mullion from Sayers Hill
(Diagrams normal to mullion axis, arrow points north)

Figure 75

The pattern of the non-undulose grains may be due to partial recrystallisation, relieving the strain in selected crystals, in which case the fabric reflects the superposed deformation. The pattern may be due, alternatively, to disorientation due to annealing recrystallisation. But however the fabric developed, the Sayers Hill mullion has a sub-fabric similar to the fabric of the Porcupine Hill mullion and supports the inference that mullions of the Porcupine Hill Style are a single class of structures.

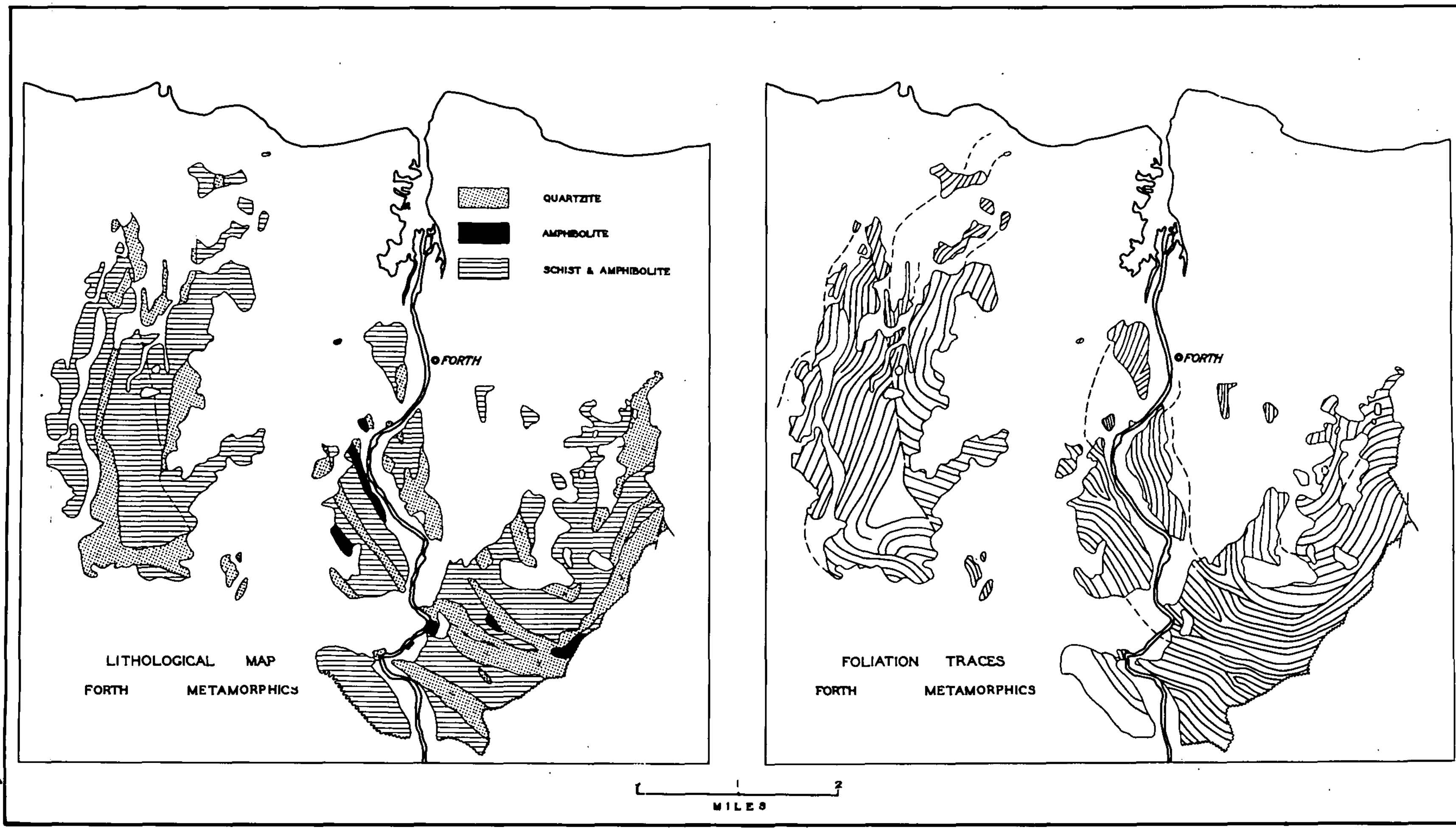
General Precambrian structure

The most striking feature of the Forth Metamorphics is the parallelism of S-surfaces of inferred different origins, and the consequence of this, which is the concordance of lithological layering with the young, dominant foliation, S2.

Lithological alternations on a scale between one and twelve inches thick forms a layering in schists and quartzites. Thicker alternations in the quartzites resemble flaggy bedding. This foliation is probably bedding. In many bodies of quartzite the bedding is parallel to the boundaries of the bodies and is parallel to the S2 foliation in adjacent schists. In schists, bedding is preserved only in fold hinges and is obliterated in intervening areas.

Lithological alternation on a scale between one-quarter and three inches thick in amphibolites is due to layers rich in garnet, chlorite, actinolite, or sometimes albite, and results from syntectonic metamorphism. This layering is generally parallel to S2, but at Goldie Creek is folded about S2 as axial plane.

The belts of schist and amphibolite are about half-a-mile wide and are separated by belts of quartzite. Within the schist belts there is an alternation of lithologies from muscovite-albite schist to garnet-biotite schist to layered quartzite and schist to banded amphibolite. The succession across the belt near the mouth of Goldie Creek has a repetition of lithologies which is not systematic, and is not due, for example, to isoclinal folding of wavelength equal to the width of the belt. If a cross-section of a limb of the Forthside Antiform is drawn, there is no systematic repetition of lithologies which might be explained as due to isoclinal folding. If isoclinal folding is present there should be occasional major lithological closures or regions in which S2 is at a high angle to earlier foliations. These do not occur. If a single quartzite band is followed it terminates, not as a plunging fold nose, but as a pointed wedge. This suggests that each lithological unit is to be regarded as a tectonically emplaced, possibly rootless body. There



QUARTZITE
AMPHIBOLITE
SCHIST & AMPHIBOLITE
FORTH
LITHOLOGICAL MAP
FORTH METAMORPHICS
FORTH
FOLIATION TRACES
FORTH METAMORPHICS
1
2
MILES

has been rotation of early planar structures into parallelism with S2. In figure 76 the map trace of S2 has been reconstructed as objectively as possible and comparison with the lithological map shows that there is a close correspondence between lithological boundaries and S2.

Because of the extensive and almost complete transposition of earlier planar structures into parallelism with S2, there is an overall "pseudo-monoclinic" symmetry of fabric. Mesoscopic triclinic fabrics in which structural elements of several phases interact at high angles are observed in only restricted areas such as at Picnic Point in the Ulverstone Metamorphics. This structural pattern is similar to that found in other areas of the Precambrian of Tasmania. At Cradle Mountain recent work by the Geological Survey shows that there are two periods (at least) of folding with the axial planes in each period being parallel over wide areas. The axes of each phase are nearly parallel and the resultant patterns of refolded early axes and superimposed late axes are indistinguishable. Structures of the two phases interact at a high angle only in narrow zones about 300 feet wide and several miles apart. R.D. Gee (1963, pers. comm.) has described an area in the South-West Highlands of Tasmania in which two periods of deformation are inferred from textural studies but axes and axial planes of each phase are parallel over a wide area - in only one outcrop do refolded folds occur.

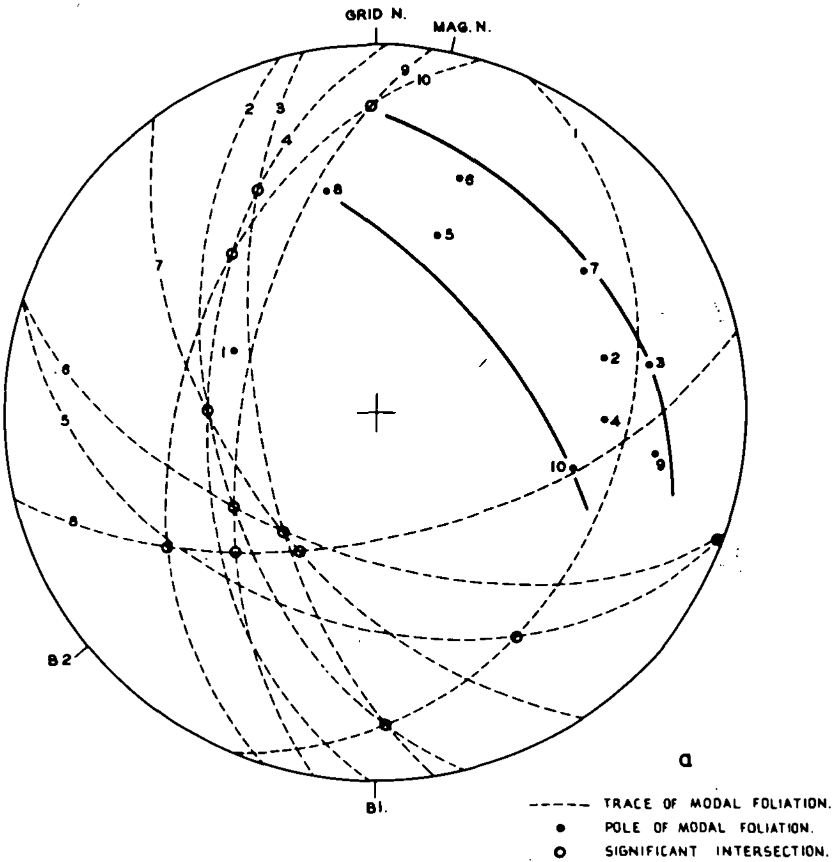
Post-metamorphic structures

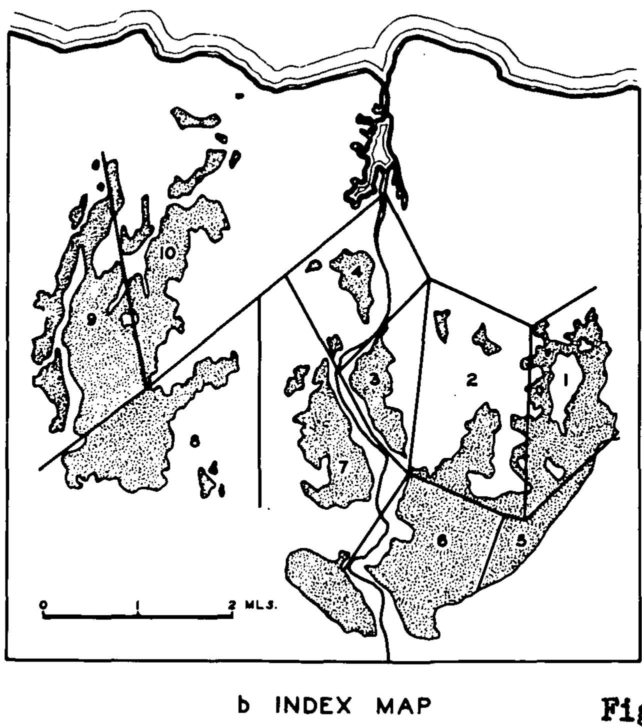
The post-metamorphic structures are outlined by S2 and lineations of the Porcupine Hill type (figure 77). The deformation consists of flexural refolding of S2 on a scale rarely exceeding twelve inches amplitude, with associated cleavages and joints only weakly developed.

The modal S2 for a number of subareas has intersections in a girdle dipping west, so that refolding was not confined to a single episode as it is, for instance, at Frenchman's Gap, where R.D. Gee (pers. comm.) has found a significant concentration of such intersections.

However, two large folds of S2 are considered definitive of the superposed deformation. A large open fold at Spalford, near the western margin of the Metamorphics, plunges southeast on an upright axial surface, corresponding in style with Tabberabberan folds of the younger rocks.

North of Porcupine Hill, near the eastern margin of the Metamorphics, a large open fold refolds S2, and corresponds in direction and plunge with an associated fold in the overlying Ordovician rocks. The crestal trace is sharply deflected at the unconformity, reflecting





b INDEX MAP

Figure 77

differences in initial orientation of S2 in the basement and bedding in the conglomerate, as in a hypothetical example cited by Ross (1962), and discussed by O'Driscoll (1962, p.165).

The post-metamorphic folds are of small wavelength, and appear as minor crenulations of pencils, rods, and foliation in the schist. In the quartzite, minor folds are infrequent, known only in thinly laminated rocks, and well developed only on Porcupine Hill within a few hundred feet of the base of the Ordovician.

Folds in schist and amphibolite at the mouth of Goldie Creek are confined to a zone about 100 feet thick on the south side of a reef of quartzite. The style is carinate to zig-zag, with a wide-spaced axial strain-slip cleavage. The folds root on the quartzite, the schist-quartzite boundary being a smooth wall without any evidence of folding of this type or orientation. Deformation in this area, and probably generally, was therefore of a competent-incompetent flexural type, with small-scale crumpling confined to the incompetent schist.

The Precambrian-Ordovician relationships at Porcupine Hill show the folds of northerly trend are post-Ordovician, and these, together with the folds trending southeast, are assigned to the Tabberabberan.

CHAPTER 11

PRECAMBRIAN OROGENIES

CHAPTER 11

Precambrian Orogenies

Introduction

The term Frenchman Metamorphic Period was introduced by Spry (1957b, p.106) for an inferred deformation period between the "older" and "younger" divisions of the Precambrian. The term Metamorphic Period was used "as it is mostly the results of regional metamorphism which distinguish these rocks" (pers. comm.). In 1962, Spry (p.124) introduced the term "Frenchman Orogeny" for the series of metamorphic and tectonic events which produced the metamorphism and characteristic tectonic style of the Franklin Group of Central Tasmania (which resembles in these characters the Forth Metamorphics of the Dial Range area). Spry felt that the Frenchman Orogeny preceded the deposition of the slightly metamorphosed "younger" division of the Precambrian but recognised that the evidence (1962, pp.121-122) is not conclusive.

In the Dial Range area the Precambrian may be divided into two divisions, a lower and an upper division. These terms are used in preference to Spry's "older" and "younger" as they carry no implications of relative age and are descriptively accurate in that the upper division everywhere overlies the lower. The Upper Division is represented by the Rocky Cape Group. The Lower Division consists of the Forth and Ulverstone Metamorphics. The boundary between the two divisions in the Dial Range area is a thrust, the Singleton Thrust.

The Singleton Thrust is the major structure in the Precambrian of the Dial Range area, and a priori could be a thrust, thrusted unconformity, or an unconformity. The nature of the structure is examined by comparison between the two divisions of lithology, metamorphic grade, fold styles, and tectonic successions. Further evidence is provided by the general relationships of the divisions at their boundary and by the nature of the boundary itself.

It is concluded that the boundary between the Upper and Lower Divisions of the Precambrian is a large thrust. While recent work in the Central Highlands of Tasmania suggests the boundary is a thrusted unconformity there are no indications of this in the Dial Range area.

Relationship of the Precambrian Divisions

Distribution of Conglomerates: Within the Rocky Cape Group immediately west of Goat Island are several layers of conglomerate at the bottoms of thick sandstone beds. They are probably the one layer repeated by strike faulting. The pebbles are quartzite, ellipsoidal in shape, with some of the ellipsoids fractured and broken. The matrix is coarse sandstone with a clastic texture.

Similar conglomerates are known from the Rocky Cape

Group in other parts of Tasmania, such as at Black River on the western North Coast and Pieman Heads on the northern West Coast. In the late Precambrian Jane Dolomite of the South-West Highlands, Spry (1962, p.126) records pebbles of lithology similar to underlying metamorphic rocks. At Mt Remus the writer has found that correlates of the Rocky Cape Group contain beds of breccia consisting of fragments of foliated quartzite apparently derived from the underlying Metamorphics.

The pebbles in all these conglomerates are metamorphosed foliated rocks. They indicate a period of sub-aerial erosion of a metamorphosed terrain occurred prior to deposition of the Rocky Cape Group. However, similar pebbles occur in the Spalford Conglomerate in the Ulverstone Metamorphics. The hypothesis that identifies this erosion period with the base of the Rocky Cape Group is therefore no longer tenable.

<u>General Lithologies</u>: There is a great contrast in the arrangement and nature of lithological units between the Lower and Upper Divisions. In the Lower Division lithological boundaries are almost invariably parallel to the tectonic surface S2. Older S-surfaces are preserved mesoscopically only as relicts in "sheltered" areas of pelites at Goat Island, as tight isoclinal folds at Picnic Point and Gawler, or as detached fold cores at Forth.

S2 is a transposition foliation controlling lithological layering. In pelitic rocks it is a schistosity formed by alignment of coarse muscovite and biotite. Foliae are mesoscopically distinct at Abbotsham but interfolial spacing decreases toward the centre of the garnet zone and at Forth is only visible microscopically. In the chlorite-grade rocks S2 is a penetrative layering of quartz and chlorite. In quartzites the foliation parallel to S2 is formed by the dimensional orientation of muscovite and by the optical and dimensional orientation of cataclastically-formed grains of quartz.

In the Rocky Cape Group laminations in mudstones are usually preserved although in some zones they are obliterated by one of a group of axial-surface structures denoted collectively S1. S1 is a crenulation cleavage in many places with recrystallised sericite and chlorite arranged along cleavage planes. The quartzites retain clastic textures with negligible alteration except in zones which contain mesoscopic boudinage.

Although in general the Metamorphics range from low to medium grade and the Rocky Cape Group is almost completely un-metamorphosed, or else "comparatively unmetamorphosed", there are some low grade rocks within the Metamorphics and some higher-grade rocks within the Rocky Cape Group which appear to be "midway between the 'older' and 'younger' (divisions) in their degree of deformation, and the contacts between some 'older' and 'younger' types......are not sharp" (Spry, 1962, p.123).

The differences in metamorphic grade and in texture are well-marked in the Ulverstone area and at Mt Remus in the Central Highlands, two places where the two divisions are found in contact. Spry (1962) as a result of Tasmania-wide investigations considered that the lighological differences between divisions are sufficiently well-marked to justify sub-dividing the Precambrian on this basis throughout Tasmania. While he considers that such a large-scale, State-wide lithological contrast is best explained in terms of an unconformity representing a regionally-extensive period of tectonism, it can also be explained in terms of a large-scale thrust which has juxtaposed rocks deformed in different tectonic environments. While the lithological contrast indicates different degrees of deformation in the two divisions it does not establish different times of deformation.

Tectonic Styles: The Lower Division of the Precambrian contains the Forth and Ulverstone Metamorphics. These two assemblages are similar in tectonic style and inferred tectonic history, there being only minor differences between them of the nature of metamorphic grade and primary lithology. There is a great contrast in tectonic style between the Metamorphics and the Upper Division of the Procambrian, the Rocky Cape Group.

As discussed previously, the Lower Division has lithological boundaries controlled by the tectonic S-surface S2. In the greater part of the area of outcrop, earlier foliations and lineations are rotated towards parallelism with S2 and the structure is dominated by S2 and (S1, S2) linear structures and has a "pseudo-monoclinic" symmetry due to transposition of inherited elements. There is one small area, termed a "triclinic zone", at Picnic Point where structures of several phases interact at high angles. The grain fabric is everywhere triclinic and cleft girdles are a common occurrence. The semi-angle of the cones is presumably the angle between the inherited orientation of optic axes and the axis of superposed rotation.

In a preliminary study of the "triclinic zone" at Picnic Point, A.H. Spry (pers. comm.) has found an early lineation with associated girdle of optic axes of quartz has been refolded about vertical axes, suggesting two generations of movement with the kinmekinematic _a_ axis in the second phase being near horizontal. At Goat Island the latest phase of penetrative deformation is deduced to be biaxial with the principal component of strain near horizontal.

The S2 foliation and associated structures swing in a broad arc convex south, the arcuation being due to post-metamorphic folding, probably Tabberabberan.

The Upper Division of the Precambrian consists of the Rocky Cape Group and has suffered two periods of deformation. Folds of the first period are disharmonic, near-isoclinal ("interfolial folds") with a number of different axial surface structures. These include fracture cleavage and slaty cleavage in mudstone and crenulation cleavage in phyllite and are grouped together as S1. The folds are of between ten and twenty feet in wavelength with axial surface foliations on the limbs being sub-parallel to bedding. In quartzites the most commonly occurring minor structure is a planar "concentric jointing" which is almost parallel to bedding. From the asymmetry of the minor folds it is probable that the region examined, between Goat Island and Blythe Heads, lies entirely within one limb of a major reclined fold with antiformal closure to the west. This fold limb has, however, been broken up and by imbricate faulting in the second phase of deformation.

Second phase deformation resulted in an imbricate or schuppen structure. Folds are disharmonic, asymmetrical, and east-facing. The majority of closures observed are antiforms with abbreviated eastern limbs terminated on strike faults. At Goat Island a distinctive lithology is repeated three times by strike faults in as many hundred yards. At Sulphur Creek three such faults are known, and two inferred, spaced at intervals averaging 200 feet. In some regions rounded folds are absent with the bedding forming zig-zags in plan. On maps or air photographs the zig-zags resemble zig-zag folds with faulted axial planes. However, there is no reversal of sedimentary facing across the fault so the zig-zags are not folds but juxtaposed fault blocks between which bedding has been rotated en bloc. Bedding in each faulted-bounded block is rotated with respect to bedding in neighbouring blocks.

It is inferred that the strike faults are splays arising from a large thrust fault at depth. The strips between splay faults are sometimes rotated and as a unit and sometimes disharmonically folded.

Folds of the first generation at Sulphur Creek pitch south at fifty degrees in a mean axial plane near 66NW016 (plunge is 44-222). Axial planes of second generation folds are oriented near 74NW035 with the fold axes pitching fifty-two degrees south, yielding a modal plunge of 49-236. (This is for (S0, S2) folds, not (S1, S2) folds). The orientations of folds of the two phases are close together at Sulphur Creek and the two phases are distinguished on style and on the rotation of early planar elements in second generation folds. At Blythe Heads the interaction of the two phases may be demonstrated in terms of the rotation of early linear elements. These lineations may be "unrolled" by unwinding the second-generation fold about beta (0, 2) not beta (1, 2) indicating that the fold formed by flexural-slip along bedding.

At Sulphur Creek the axes of the two generations of folds are near-parallel, pitching about fifty degrees south in the bedding.

Current work by R.D. Gee shows that at Blythe Heads the distributions of axes are skew and overlapping with pitches of early folds ranging from forty to beyond ninety degrees south, and pitches of late folds ranging from ten to sixty degrees south.

Unwinding the second generation structures is a conjectural procedure as the amount of rotation that occurred in this period of deformation is unknown. However, unwinding by the small amount of forty degrees (by a clockwise rotation looking down the (0, 2) axis) the regional dip becomes 81SE248 with bedding facing right way up and the axial planes of first generation folds return to 90SE228 and modal B (0, 1) becomes 40-229. This is a reasonable picture of the situation before formation of the imbricate schuppen structure.

Relations of Divisions at Boundary: In the Gawler River west of the township of Gawler the base of the Rocky Cape Group is a sandstone at least twenty feet thick which is overlain by mudstone. The sandstone dips south-west. In the underlying Ulverstone Metamorphics there is a belt of quartzite flanked on either side by schist, the lithological boundary being parallel to the transposition foliation S2 which is near-vertical and strikes south-west. Mullion structures in the quartzite plunge near-horizontal (less than fifteen degrees) in S2. This structure in the Metamorphics continues to within 400 yards of the base of the Rocky Cape Group but is then sharply deflected in plan, both the foliation and lineation trends swinging in an arc of small radius. The foliation and lineation trends in the Lower Division are truncated at the base of the Upper Division, the angle of unconformity being about fifteen degrees.

This truncation implies either a fault or an unconformity. The deflection of structures in the Lower Division suggests movement along the boundary in the sense of upper plate moving south.

On the South Road from Penguin to Ulverstone, a few hundred yards north of Singleton's Point (a point in the Leven River two miles west of Ulverstone) the boundary between the two divisions of the Precambrian is exposed in a road cutting. The schistosity in the Metamorphics dips steeply west and is truncated sharply upwards against sandstones of the Rocky Cape Group which here dip gently east. The boundary is a structural and metamorphic hiatus.

At Goat Island the boundary between the two divisions outcrops on the shore platform. It is repeated by Devonian strike faulting in another basement wedge to the east.

The dominant foliation, S2, of the Metamorphics is near vertical and striking north-west while the boundary is gently dipping at between fifteen and forty degrees and has variable strike. The foliation in the metamorphics together with a lithological layering transposed into parallelism with the foliation is truncated upwards at the boundary.

The overlying Rocky Cape Group has a homoclinal structure with beds dipping west and overturned. This general structure continues into areas where the exposed outcrops must be almost directly underlain by the boundary. The homoclinal structure in the Rocky Cape Group is therefore truncated downwards by the boundary. The boundary between the two divisions of the Precambrian is therefore a thrust.

Nature of the Boundary between Divisions: The boundary between the Upper and Lower Divisions of the Precambrian is exposed at several places at Goat Island where it is a weathered gouge only a few inches thick.

The gravel-covered neck joining Goat Island to the mainland is underlain by a chaotic breccia containing blocks of both Metamorphics and Rocky Cape Group. The blocks range from three to twenty feet in length and are tabular in shape. The boundary of each block against its neighbours is a clear-cut fault with negligible matrix between blocks. There is no clastic matrix. In detail the blocks form a patch-work quilt arrangement in which the S2 foliation of the Metamorphics is differently oriented in different blocks and S2 in any block is truncated at the edge of the block. East of Goat Island the chaotic breccia consists principally of slabs of the Metamorphics but west of Goat Island the slabs are mainly Rocky Cape Group. However, boulders of each type are intermingled in each area. This chaotic breccia has similarities with the Chaos structures (particularly the Riggs Chaos) described by Kupfer (1960) which overlie thrust faults in California.

The thrust between the Upper and Lower Divisions of the Precambrian truncates structures of the youngest period of metamorphism in the Lower Division and truncates structures of the youngest period of folding in the Upper

Division. The thrust was probably active at the time of second generation folding in the Rocky Cape Group, that is, pre-700 million years B.P.

At Mt Remus the writer has described a fault wedge of Rocky Cape Group which occurs as a thrust slice with Metamorphics above and below. This imbricate arrangement is truncated stratigraphically at the base of the Cambrian Dundas Group so that the Rocky Cape Group and the Metamorphics were faulted together in Precambrian time.

Tectonic Succession

The two divisions of the Precambrian have been folded together in the Tabberabberan Orogeny. They are in faulted relation to each other, the faulting accompanying the second phase deformation of the Rocky Cape Group. There is, however, no evidence of a widespread Precambrian period of folding common to the two divisions.

At Goat Island there is a fault zone crosses the island which post-dates the S2 foliation in the Metamorphics. Along the footwall of this fault is a narrow zone of coarse-spaced crenulation cleavage which post-dates S2 and is probably not Tabberabberan. This cleavage may have been formed during one of the periods of folding in the Rocky Cape Group. The restricted, minor deformation of the Metamorphics is consistent with extensive folding in the

Rocky Cape Group only if there is an active decollement separating the divisions. The crenulation cleavage in the Metamorphics is therefore correlated with the second phase of deformation in the Rocky Cape Group. With this correlation the Precambrian structural history is as listed below.

Tectonic Movement	Lower Division	Boundary	Upper Division
Penguin Orogeny	Crenulation cleavage of restricted distribution	Thrust	Second generation folding and formation of a schuppen structure
Frenchman Orogeny	Second phase of deformation and metamorphism. Formation of transposition foliation S2	Transition?	First generation folding. Metamorphism of low grade in some areas
	First phase deformation and metamorphism		

CHAPTER 12

THE TYENNAN OROGENY

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The Tyennan Orogeny

Introduction

The Tyennan Orogeny was defined by Browne (1949) as that tectonic movement represented by the unconformity between Ordovician rocks above, and supposedly Cambrian rocks below, in the Tyenna Valley of south-western Tasmania. Carey and Banks (1954) identified the rocks below this unconformity as pre-Cambrian and re-defined the Tyennan Orogeny to mean the movements immediately preceding, accompanying and immediately following deposition of the Dundas Group.

In that which follows, the name Tyennan Orogeny will be used in a sense close to that of Carey and Banks, to mean those movements which accompanied deposition of the Dundas Group and which had terminated by the time of inception of Ordovician (Junee Group) sedimentation. The interval of erosion between the top of the Dundas Group and base of the Junee Group will be termed the "Jukesian" interval and regarded as falling within the time span of the Tyennan Orogeny.

The type and extent of movement synchronous with Dundas Group deposition, and the question of whether the Jukesian interval represents a period of tectonic movement (the "Jukesian Movement" of Carey and Banks) is considered here.

It is concluded that tectonic movements of considerable magnitude accompanied deposition of the Dundas Group and that deposition was concluded by folding and erosion during a Jukesian Movement. Two periods of deformation and erosion are recognised - the Hardstaff Movement of Middle Middle Cambrian time and the Jukesian Movement ranging in time from Lower Upper to Middle Upper Cambrian.

Lobster Creek Volcanics

The Lobster Creek Volcanics form an axial belt of massive rocks of igneous derivation. Belts of similar rocks occur in the Dundas Trough in other parts of Tasmania. Burns (1961a) considered one thick belt to be an accumulation of water-laid pyroclastics. However, a related belt has the form of a large sill intrusive at the base of the Dundas Group (Burns, 1964). Another belt of volcanics has been considered by Campana et al (1958) to be effusive fragmentals underlying higher formations of the Dundas Group. Solomon (1960) suggests the volcanics in one area are remnants of submarine volcanoes.

One or several of these hypotheses may be applicable to the Lobster Creek Volcanics. They are similar to volcanics in other thick belts in that the rocks are coarse-grained, acidic in composition, massive and largely structureless. The volcanics either underlie the Cateena Subgroup disconformably or are an intrusion through them of laccolithic form. The time of emplacement on either view was pre-Middle Cambrian as the volcanics are overlain unconformably by the Barrington Chert.

South-east of the Dial Range area Burns (1957a) found a belt of volcanics of similar petrological type and similar stratigraphic position to the Lobster Creek Volcanics. As this belt contains lapilli tuffs and agglomerates it is probable that the Lobster Creek Volcanics are also "effusive fragmentals" in the terminology of Campana. They have, however, a ridge-like form, which suggests that they are a buried volcanic ridge. The metamorphism of mudstones adjacent to the volcanics in one area, cited by Hughes (1953) as evidence of their magmatic emplacement, is a hydrothermal effect and post-dates a Devonian slaty cleavage.

Cateena Point Subgroup

The Cateena Point Subgroup contains two areally segregated lithological assemblages of the same age. At the southern end of the Dial Range Trough, in the vicinity of Sprent, the subgroup is represented by thick-bedded claystones with minor cherts and limestones. The claystones are thick-bedded, massive and structureless. At the northern end of the Trough, west of Ulverstone, the Subgroup is represented by a sandstone-mudstone assemblage. This consists of inter-laminated and interbanded mudstone and siltstone or fine sandstone. The sandstone-mudstone and claystone assemblages interfinger over a zone about two miles wide.

Claystones or the type occurring at Sprent are not common in the Dundas Group. Taylor (1954, see Banks 1956, pp.179-180) considered a similar assemblage to be a group apart from the Dundas Group. The transition from one assemblage to the other could reflect distance from a common source, as described by Hsu (1960). Alternatively the sandstone and mudstone could have been deposited along the track of currents travelling down the axis of the trough, and claystones could have been deposited on the flanks of the trough from the same or a different source.

Coarse sandstones and mudstones are of restricted occurrence. Rocks of this grain size occur at two places within the sandstone-mudstone assemblage near Cateena Point and two horizons, probably the same ones, occur in the Gawler River about three miles to the south. The rocks form macro-graded units which are groups of twenty to thirty beds totalling about 100 feet in thickness. In each group of beds the grain size and thickness of individual beds decreases upwards. The macro-graded units are succeeded upwards by "normal" sandstone and mudstone and recur at intervals of 1500 feet in the stratigraphic column. An analogous cyclic variation in grain size in the Dundas Group of the West Coast of Tasmania has been termed by Carey and Banks (1954) and Banks (1956, p.204) "megacyclothems". Eight megacyclothems are recognised on the West Coast, each having a conglomerate-rich section followed upwards by first arenites then lutites. Banks (1962, p.143) interprets the cycles in terms of "tectonic instability and variation in height of the source area". However, in the Dial Range area the progressive decrease in grain size upwards through the macro-graded units suggests that these have been re-deposited from a source of limited volume such as a small river delta or marine embankment. The upper limit of the macro-graded unit corresponds to depletion of the source. If this is the case then the cause of slumping from the deltaic terrace could be tectonic movement but could equally well be a result of overloading. An embankment-type deposit is liable to cyclic failures which occur whenever the front of the deposit reaches a critical height or slope. The megacyclothems of the West Coast and the macro-graded units of the Dial Range do not necessarily represent tectonic or environmental changes.

Sedimentary folds in the Cateena Subgroup are interstratal open-cast folds probably formed by gravitational sliding. The folds occur only in the macro-graded horizons and it is considered that sliding resulted from the accelerated rate of deposition represented by these horizons. The rate of deposition exceeded rate of consolidation and sliding was an inevitable result. The beds slid down the depositional slope on a clay substratum to form an imbricate structure. The modal orientation of the folds does not correspond with that of tectonic (Devonian) folds in the vicinity. The axes are oriented normal to the inferred depositional slope with axial planes dipping downslope.

Currents depositing the Cateena Subgroup were directed from the northern quadrant implying a general depositional slope to the south. The distribution of the two lithological assemblages, sandstone-mudstone and claystone, is consistent with a trough oriented with long axis running north-south or north-east to south-west. The Wilsonia Volcanics thicken southward at a rate near 175 feet per mile implying a slope of this order of magnitude. The orientation of the sedimentary folds at Cateena Point implies that in the basin of deposition the southwards slope was approximately equal to the westward slope, that is, the slope across the trough was approximately equal to the slope down the trough in this vicinity. It is concluded that the Cateena Subgroup was deposited in a shallow but defined trough which had an axial slope to the south. Sediments were derived from the head of the trough, from somewhere to the north of the present coast-line. There is no evidence of contemporaneous tectonic movement.

Hardstaff Movement

The base of the Barrington Chert has been identified as an unconformity, the Hardstaff Unconformity. It represents erosion of at least 1500 feet of Cateena Subgroup in an area at Hardstaff Creek and at least 500 feet at Lobster Creek. However, in the type area of the Barrington Chert, some ten miles south-east of the Dial Range, it is probable that the amount of erosion at the base of the chert was negligible.

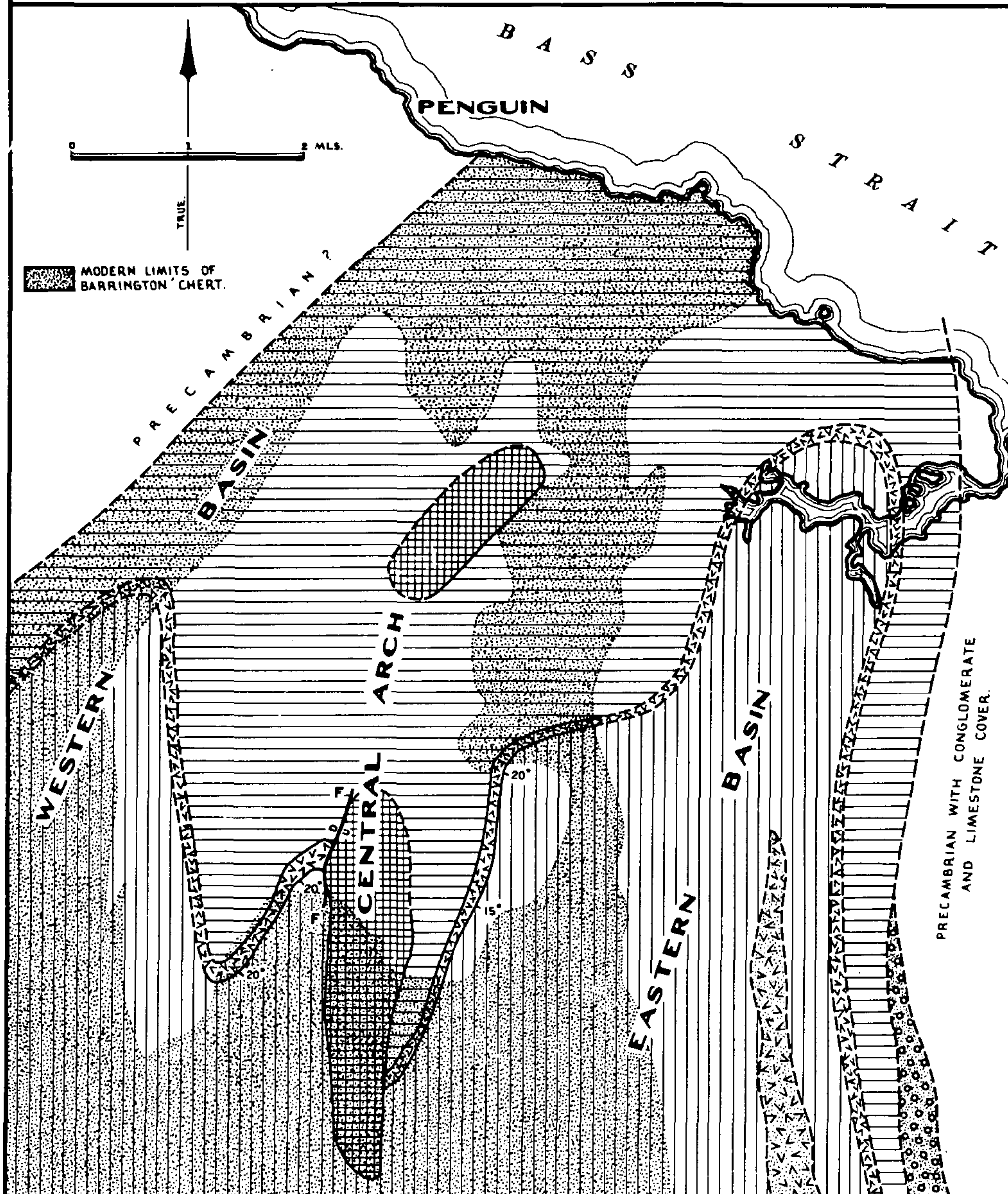
A palaeogeologic map of the base of the chert (figure 78) indicates that the erosional period represented by the unconformity followed gentle folding of the Cateena Subgroup and localised faulting. These movements are termed the Hardstaff Movement and are regarded as a phase of the Tyennan Orogeny.

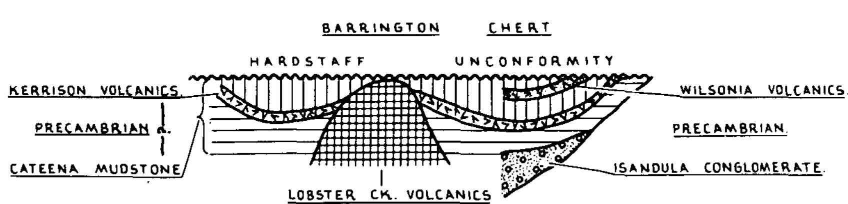
The palaeogeologic (or "sub-crop") map of figure 78, at the base of the Barrington Chert, has Tabberabberan deformation only partly unwound. The Dial Range Trough is divided into two basins, by a central "arch" of Lobster Creek Volcanics. The available data show no sedimentary features, such as variations in thickness of the Kerrison Creek Volcanics, which reflect this basin arrangement. The form is therefore due to deformation and was probably produced in a short period of time. The formations of the

Cateena Point Subgroup are "draped" over the central arch with a small fault along the western side of the arch in one place. This structure may be interpreted in two ways. First, the Lobster Creek Volcanics may be diapiric intrusives of a type described by Hunt (1932). Second, there may have been "Plains-type" folding of the Cateena Point Subgroup of the type described by Clark (1932) over a pre-existing pile of volcanics. As stated in discussion of the Lobster Creek Volcanics, the balance of probability is against the first hypothesis. "Plains-type" folds are of several different origins, some being formed during, and some after, deposition. They are characterised by their form as gentle, broad folds which coincide in position and amplitude with undulations of the basement. The folds in the Cateena Subgroup are of this general type and may have been formed by either differential compaction of sediments concurrent with deposition or differential subsidence of the basement. The latter is more probable. The movements were fairly large, the fault being a normal one with several hundred feet throw. There was considerable erosion after the movement as the base of the Barrington Chert transgresses a substantial thickness of the Cateena Point Subgroup.

It is considered that the Hardstaff Movement consisted of differential subsidence followed by erosion of highs. The most significant effect was to alter the type of sediment

MIDDLE CAMBRIAN GEOLOGY – DIAL RANGE
(AT BASE OF BARRINGTON CHERT)





DIAGRAMMATIC KEY

Figure 78

from sandstones and mudstones to chert, implying major regional changes in the environments of source and deposition. This conclusion is in general agreement with Campana et al (1958) who considered differential subsidence of basement blocks to have accompanied and controlled Cambrian deposition on the West Coast of Tasmania.

Barrington Chert and Motton Spilite

The Barrington Chert and Motton Spilite together form a distinctive lithological intercalation within the Dundas Group. The Dundas Group throughout Tasmania consists dominantly of mudstones and sandstones, acidic to intermediate volcanics, and subordinate conglomerates. The type section at Dundas contains these lithologies only. In this context, the Barrington Chert and Motton Spilite appear as interruptions to normal sedimentation. They are of restricted extent and are probably confined to the Dial Range and a region lying to the south-east.

Following the Hardstaff Movement the normal clastics were swamped by siliceous material. The mud-carrying currents were not completely cut off as the Barrington Chert contains beds of mudstones and conglomerates and much of the chert is impure or even a siliceous mudstone due to dilution with clay.

The chert is a thick tongue lying along the axis of the Dial Range Trough (figure 5). The maximum thickness shown in figure 5 is a conservative estimate and allows for the possibility that the succession on Mt Lorymer, where the chert is 4,800 feet thick, is repeated by thrusting. From the axial tongue the thickness of the chert drops away rapidly to an average of 250 feet on the flanks.

Only remnants of the Motton Spilite are preserved so the original form of this formation cannot be reconstructed. There is an abrupt cut-off on the western side that suggests that this formation may have been a thick, narrow tongue, with the region of maximum thickness adjacent to that of the Barrington Chert.

On the mesoscopic scale the chert is nappe-like with numerous inter- and intra-stratal folds, including among the former some recumbent folds with amplitudes up to three feet. An unconformity has been noted in one place. The base of the chert is the transgressive Hardstaff Unconformity so that the trough which accommodated the chert was largely erosional in origin. There is an indication of progressive overlap of the chert against a rising sea floor (figure 47). The very great thickness may be due in part to the piling-up of contemporaneous slides moving semi-consolidated chert from the flanks to the axial region of the trough.

Radfords Creek Subgroup

At the southern end of the Dial Range the Radfords Creek Subgroup is a fairly monotonous mudstone-sandstone repetitive succession. These rocks abut against the Motton Spilite with a fairly sharply defined boundary. At the boundary the Radfords Creek Subgroup contains boulders and lithic fragments derived from the Motton Spilite.

In the Sugarloaf Gorge near Gunns Plains and in the Loyotea region some ten miles to the south-west the Radfords Creek Subgroup contains a lens or lenses of quartzite conglomerate. This is a continuous framework conglomerate with well-rounded pebbles in a matrix of quartz sand and contains mainly Precambrian pebbles derived from the west. The conglomerate in the Leven Gorge occurs near the Leiopyge zone of the Lower Upper Cambrian and dates the first emergence of the Rocky Cape Geanticline on the western side of the Dial Range Trough.

At the northern end of the trough the Radfords Creek Subgroup is represented by its highest formation, the Beecraft Megabreccia. The megabreccia abuts against Precambrian basement on the west side of the trough, and from there eastwards overlies, successively, mudstones and conglomerates of the Radfords Creek Subgroup, Motton Spilite, and (at Westbank) Precambrian basement of the eastern flank of the trough. This transgression indicates considerable erosion had occurred before deposition of the megabreccia and had exposed the basement on the flanks of the trough. A palaeogeologic map, if drawn at the base of the megabreccia, would show the older formations of the Radfords Creek Subgroup confined to a narrow zone along the western edge of the trough. The trough had a pronounced east-facing asymmetry at this time.

During deposition of the Radfords Creek Subgroup the flanks of the trough were uplifted and the cover was removed - in part by gravitational sliding of marginal deposits towards the axis of the trough. The basin became asymmetrical in cross-section with a narrow down-warp adjacent to the western margin. There was considerable erosion of topographic highs. As well as narrowing, the trough probably tilted southwards. These Lower Upper Cambrian movements which are reflected in the sedimentation are considered to constitute the first phase of the Jukesian Movement.

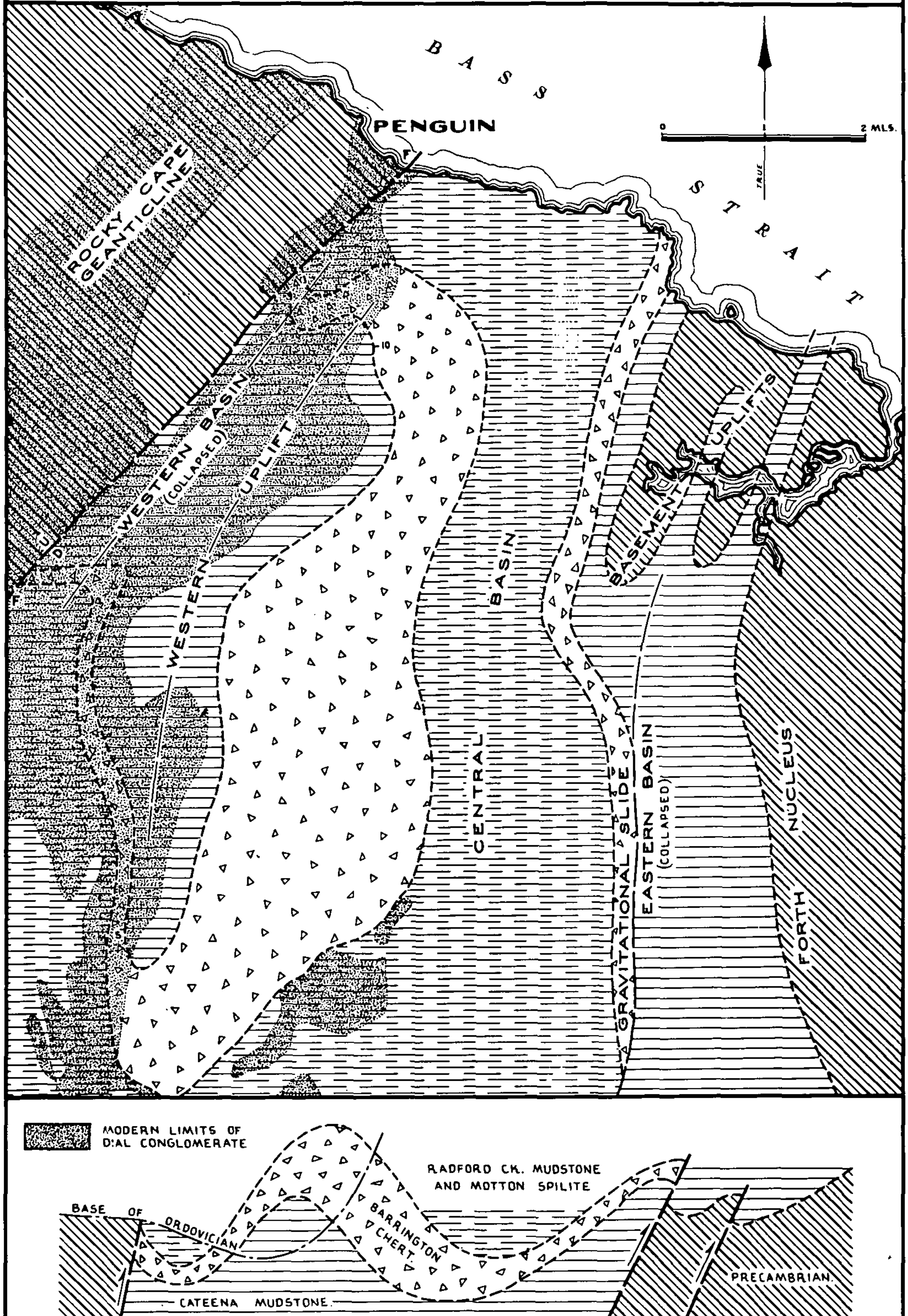
Jukesian Movement

An apparent unconformity on Mt Jukes, on the West Coast of Tasmania, was described by Hills (1914) but was discounted by Bradley (1954) as evidence of a tectonic movement. The term Jukesian Movement was re-defined by Carey and Banks (1954) to mean those movements represented by the unconformity between the Dundas and Junee Groups. An unconformity in this stratigraphic position has been reported from several Tasmanian localities (Solomon, 1962, p.321) although in some areas there is apparent conformity.

In the Dial Range the (Ordovician) Dial Range Conglomerate unconformably overlies the Dundas Group. The base of the conglomerate transgresses all formations from the base of the Dundas Group to the top. Boulders of keratophyre resembling that intruding the Beecraft Megabreccia are found in the conglomerate in one locality (Myrtle Creek, south-east of Penguin) and the bulk of the conglomerate is re-cycled Barrington Chert. Boulders of limonite from an orebody which replaces Cambrian conglomerates (Burns, 1961b) are a prominent constituent of the conglomerate.

A palaeogeologic map of the base of the Junee Group is shown in figure 79. Dundas Group sediments are lacking from the flanks of the Dial Range Trough. There is a central uplift composed of Barrington Chert which despite low limb-dips of about fifteen degrees had a structural relief approaching 1,000 feet. The fairly tight syncline at the western margin was at least partly formed during deposition of the Radfords Creek Subgroup. The palaeogeology of the eastern flank of the Dial Range Trough is

LOWER ORDOVICIAN GEOLOGY — DIAL RANGE
(AT BASE OF DIAL CONGLOMERATE)



DIAGRAMMATIC KEY

Figure 79

conjectural but there is a possibility of low-angle thrusts at the edge of the thick wedge of Barrington Chert.

At the time of deposition of the Beecraft Megabreccia, which contains two suites of allochthonous lithologies apparently derived from opposite sides of the trough, the trough was topographically negative with currents travelling from the north. However, in Lower Ordovician time the region was mainly topographically positive with respect to the flanks. It is therefore concluded that sedimentation in the Dial Range Trough was halted by growth of the central anticline. The chert-granule conglomerates in the Teatree Point Megabreccia may bear witness to erosion of chert in early stages of this uplift.

The period of folding, the Jukesian Movement, began during Lower Upper Cambrian time during sedimentation of the Radfords Creek Subgroup and was concluded by early in the Ordovician.

Conclusions

The movements preceding the deposition of the Dundas Group include the Penguin Orogeny which was pre-700 million years B.P. The Tyennan Orogeny of Carey and Banks (1954) is re-defined to exclude movements preceding and to include movements during and immediately after, deposition of the Dundas Group.

Two phases of the Tyennan Orogeny are recognised in the Dial Range, the Hardstaff Movement and the Jukesian Movement.

The Hardstaff Movement occurred in Middle Middle Cambrian time with differential subsidence and minor normal faulting. Movements were followed by erosion which stripped hundreds of feet of Cateena Point Subgroup from highs before deposition of the Barrington Chert.

The Jukesian Movement commenced in the Lower Upper Cambrian during deposition of the Radfords Creek Subgroup. Immediately before, or during deposition of the Radfords Creek Subgroup the axis of the trough was tilted southwards so that the Subgroup is strongly transgressive over older formations. The cover on the flanks of the trough was stripped from the basement and transported into the trough, in part by mass movement. Sedimentation was halted by the growth of a broad anticline in the axial portion of the trough which was flanked by synclines. The western syncline commenced development during sedimentation and its final form was asymmetrical facing east reflecting the overall shape of the trough. Intrusion of dykes and stocks of keratophyre and formation of a limonite orebody at the Iron Cliffs by alteration of Precambrian haematite ore accompanied the Jukesian Movement which had terminated by Lower Ordovician time.

CHAPTER 13

THE TABBERABBERAN OROGENY

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Introduction

The Tabberabberan Orogeny was first recognised in the Tabberabbera district of Victoria where rocks of inferred Upper Devonian age overlie Silurian rocks unconformably (Swaminath, 1958). A stratigraphic break correlated with this orogeny extends into southern New South Wales where Upper Devonian rocks unconformably overlie Middle Devonian. In Tasmania the Tabberabberan Orogeny has been identified as that movement period following the deposition of the Lower Devonian Spero Bay Group (Banks, 1962, p.184) and preceding the deposition of the Upper Devonian Eugenana Beds (Banks and Burns, 1962, p.185).

The Orogeny was a widespread event in Australia causing folding and terminating geosynclinal deposition in Tasmania, Victoria, and southern New South Wales. In New South Wales it is followed by deposition of shallow marine or lacustrine deposits, in Victoria by lacustrine deposits and in Tasmania, except for the accidentally-preserved cave deposits at Eugenana, it was followed by a long period of erosion.

The Tabberabberan Orogeny is the principal Palaeozoic movement episode in Tasmania with granite intrusions occurring during this episode. In the Dial Range Area two distinct movement periods are recognised and termed the Eugenanan and Loonganan Movements respectively. The Orogeny is dated as Middle Devonian.

Stratigraphic Dating

In the Dial Range it has been possible to date the Tabberabberan Orogeny as Middle Devonian.

Deposition of the Junee and Eldon Groups and correlates extended from the Ordovician to Lower Devonian. Throughout Tasmania these rocks are strongly folded and faulted in contrast with rocks of the Permian System which record tilting and faulting only. The hiatus between the Siluro-Devonian Eldon Group and the Permian System was equated by Carey and Banks (1954) with the Tabberabberan Orogeny but there was some uncertainty in that the stratigraphic break, extending from Lower Devonian to Lower Permian, spans the time range of both the Tabberabberan and the Kanimblan Orogenies.

At Point Hibbs Banks (1962, pp.184-185) found the Spero Bay Group unconformably overlying Cambrian rocks and suggests that the absence of the Eldon Group is to be explained as uplift and erosion before deposition of the Spero Bay Group (Solomon, 1962, p.323). This dates one movement period as between the Eldon Group (Lower Devonian) and Spero Bay Group (Upper Lower Devonian or Lower Middle Devonian). The Spero Bay Group is tilted at high angles in contrast to horizontal Permian rocks in the vicinity, suggesting a second movement period between Lower Middle Devonian and Permian.

At Eugenana the Upper Devonian Eugenana Beds overlies, unconformably, the Gordon Limestone. The disoriented slabs of foliated limestone in the boulder beds show that the first phase of Tabberabberan deformation preceded the Upper Devonian.

Tectonic structures are absent from the Eugenana Beds, excepting minor joints which are probably of Tertiary age. There is no occurrence of types or styles of deformation corresponding to the Tabberabberan Orogeny. The Eugenana Beds therefore post-date the second and third phases of Tabberabberan Movement.

The Tabberabberan Orogeny occurred in the interval between the deposition of the Eldon Group and the Eugenana Beds, that is, in the Middle Devonian. This date agrees with geophysical dates of granites emplaced during the Palaeozoic orogenesis. In particular, the Kanimblan Orogeny (late Carboniferous) of New South Wales has had no detectable effect in Tasmania.

Tabberabberan Structures.

Introduction: In earlier chapters structures identified as Tabberabberan have been described from Precambrian, Cambrian and Ordovician rocks. The identifications have been based upon order of development in multiply folded terrains, on profile and orientation (tectonic style), or on coincidence of basement structures with structures in younger rocks. The Tabberabberan structures so identified have a regularity which confirms their identification.

It will be concluded that two distinct phases of movement occurred. The first, or Eugenana phase, produced fairly regular folds with northerly trend. The second, or Loonganan phase, superposed oblique crossfolds which have north-east trends. The two phases are closely related in a time but there is no direct evidence of contemporaneity. The two phases appear to have been distinct and separate events. The Eugenanan stress-field had axial or orthorhombic symmetry, the Loonganan stress-field was probably of axial symmetry.

Eugenana: At Eugenana the large open folds of the Melrose Basin and neighbouring anticlines pass downwards into the contiguous Forthside Antiform in such a way as to indicate that the Ordovician and Precambrian rocks were folded together. The Ordovician mantle in this area is a thin layer effectively "fused" to the Precambrian basement.

In the Ordovician Gordon Limestone, three movement periods are recognised.

The first movement resulted in similar folding with an axial surface foliation oriented (at the present time)

60E357. Folded chert lenses, dolomite and calcite boudins, and deformed fossils yield fold axes parallel to kinematic b and oriented 23-162.

The second phase was a conjugate-style refolding of the foliation about paired axial "knick" surfaces which curve cylindrically about the fold axis and which intersect in a line lying in the foliation and parallel to the fold axes which are modally 10-180. One group of folds is asymmetrical (only one set out of the conjugate pair of knick planes is developed) with a modal axial plane 35SW172. However this is a poorly defined maximum and, in fact, axial surfaces are shears of several kinds. The orientation of the principal structural elements is as tabled below.

	Vertical shears	Horizontal shears	Oblique shears
Median	60E357	15W357	60W354
Mode	65E360	22W004	70W354

In view of the quantity and type of data available, the median is probably better measure of central tendency than the mode.

The third phase of movement resulted in minor folding of the foliation with steep axial plunge. The median axis is 50-065 which corresponds to an axial plane of 76N083.

The second generation structures are of a distinctive style. Oblique shears and accompanying oblique-shear folds are the dominant type. These shears curve cylindrically about the fold axes and in higher parts of the folds become asymptotic to the foliation. In these higher parts the folds have near-vertical axial surfaces. There are a few horizontal shears that intersect the oblique shears to form conjugate folds at their mutual intersection. The orientation of the conjugate folds indicates shortening in a vertical direction but the higher parts of the oblique-shear folds do not match this system as reproduced experimentally by Paterson and Weiss (1962). It is probable that the folds were not all formed at the one time as is indicated by the complex succession of lineations on the shear planes. The anomalies in the fold style have possibly resulted from folding occurring at several times during rotation of the stress field.

It is inferred that the first-phase folds were formed with kinematic <u>ab</u> near 90E001 and kinematic <u>b</u> near 30-172. In the second phase of movement, the foliation was possibly rotated about the second-generation axes 10-180 to the present orientation 60E357 at the same time that the regional folding occurred that formed the Melrose Syncline. Second phase folds developed with kinematic <u>ac</u> being 80N270 and <u>b</u> as 10-180. The third phase was superposed at an inferred later time with kinematic <u>b</u> as 50-065 and <u>ac</u> oriented 40SW335.

The movement episode corresponding to the first generation folds at Eugenana is termed the Eugenanan Movement. In the terrain east of the Dial Range folds of this phase have an axial slaty cleavage in mudstones and a fracture cleavage in sandstones of the Junee Group, a slaty cleavage in mudstones of the Dundas Group, and a late strain-slip cleavage (fracture cleavage of Spry, 1962, fig.5b) in Precambrian schists.

The second phase folds at Eugenana are assigned to the Eugenanan Movement on orientation alone. The flexural style suggests a faster rate of deformation or lower confining pressures than in the first phase. Folds of the third phase are correlated with the Loonganan Movement.

<u>Sulphur Creek</u>: At Sulphur Creek the Ordovician Dial Range Conglomerate forms a thin blanket over the Precambrian basement on the western flank of the Dial Range Trough. The base of the conglomerate is an irregular unconformity along which there has probably been very little slippage, that is, the conglomerate is "fused" to basement.

The Dial Range Conglomerate is folded into gentle domes and basins. One fold has a regular cylindrical form with beta oriented 15-257 and a near-vertical axial plane. The "middle" and "east" basins are noncylindrical folds. Beta diagrams for these basins yield maxima, some of high order, oriented according to the position of the sampling area. An attempt to detect cylindrical tendencies, as departures from sphericity, by evaluating modes (plotting intersections per mode against orientation of the mode) suggested a crossing trend near 158.

The folding is accompanied by small breakthrusts which intersect near 25-249 (axis of folding of the thrusts?). The normal to in the fault planes to the direction of slip is 5-170 which is the kinematic b of faulting and which is correlated with the Eugenanan fold trend.

Joints in the "east" basin have their principal axes of strain oriented uniformly in all subareas of the fold, irrespective of the attitude of bedding. The joints are therefore post-folding and of no value in determining fold kinematics.

From the Sulphur Creek data two generations of folding are inferred. The first is identified as Eugenanan, and is indicated by thrust faults and by cylindrical tendencies in the "east" basin and has a near-vertical axial plane trending 170. A period of minor folding in the underlying Rocky Cape Group, with axes near 74-001 and axial planes 87NE171 is correlated with this phase.

The second phase of folding is named the Loonganan Movement, from the Loonganan Syncline, a regional structure of the hinterland. In the "west" basin this is represented by a cylindrical fold with vertical axial plane and an axis trending 257 (plunge 15-257). A group of minor folds in the basement with axes 59-265 and axial planes 84S275 is correlated with this phase.

The folds of each phase have axial planes of similar orientation in basement (Precambrian) and mantle (Ordovician). The axial plunges vary widely depending upon initial orientation of the folded S-surfaces. This uniformity of axial planes is a characteristic of the region and in this feature the Sulphur Creek area is typical.

Dial Range: In the vicinity of Penguin and in the northern part of the Dial Range the principal crestal trend is close to 360. A crestal trace trending 020 on Mt Dial reported by Hughes (1953) is a product compounded by superposition of tectonic folds on high initial dips. The syncline of Mt Dial is crossed near Penguin by a gentle oblique crossfold, the position of the cross-fold being dictated by the position of rapid stratigraphic thinning in the Duncan Conglomerate. One of the fold trends is near 360, the crossing trend is oblique. Folds assigned to the crossing trend were found by Burns (1960) in the platy limonite ore at the Iron Cliffs to have axes 70-112 with axial planes 90N267. The 360 trend is identified as Eugenanan, the crossing trend as Loonganan.

The Gnomon Fault, an east-west tear fault system crossing the Dial Range, is a complex structure showing evidence of multiple movement. The major fault is vertical with dextral transcurrent movement, but the minor faults have variable orientations of their fault planes and directions of slip. The strikes swing through an azimuth of ninety degrees from the main fault and the faults range in type from vertical wrenches to low-angle thrusts. The variation cannot be explained as a system of splays related to a single episode of faulting but is compatible with multiple movement or with continuing movement in a rotating stress field.

In discussion of faulting it is convenient to adopt the concept of "stress regimes" of Harland and Bayly (1958). For this purpose the trend of Eugenanan folds (north-north-west in most areas) is designated as the regional B axis, the vertical direction is designated C, and the direction at right angles to the other two is designated A.

The earliest movement on the Gnomon Fault system was probably dextral transcurrent faulting on a vertical surface striking north-west. Fault breccias of this phase are intersected by oblique-slip faults with a dextral component of strike-slip and a thrust component of dip-slip. After Bott (1959) and Harland and Bayly (1958) the succession of regimes is dextral wrench followed by dextral thrust.

The fault network occurs in the stratigraphically highest part of the area. The dextral wrench movements are correlated with localised strike (B) extension in the Eugenanan Movement, that is, they are regarded as localised primary wrench movements in a general primary thrust regime. The succeeding dextral thrust movement is assigned to the Looonganan Movement.

Mt Lorymer: A network of faults exists between Mt Duncan and Gunns Plains at the south-western end of Mt Lorymer.

Folds in Cambrian mudstones (of the Radfords Creek Subgroup in the Sugarloaf Gorge), Ordovician limestone (at the north end of Gunns Plains), and Ordovician sandstone (of the Sugarloaf Gorge) have a common axial trend of 163. The folds in the Cambrian mudstone have a modal plunge of 14-163 while in the limestone on the opposite side of the Walloa Creek Fault the folds plunge 40-163.

Folds in the mudstone are associated with vertical faults, related to the Duncan Fault in type and orientation, which have a modal orientation 45W179. They are intersected by later, low-angle thrusts of mean orientation 24SW118.

The simplest solution to the fault network is that the area has been first folded on north-south axes, then "differentially" refolded on a south-west trend. In the refolding, the minor folds in the limestone were rotated to their present plunge of 40 degrees south by wholesale rotation of the north limb of the Gunns Plains basin. Folds on the eastern side of the Walloa Creek Fault were not rotated an equivalent amount. The fault thus behaved as a strong inhomogeneity controlling deformation.

Concurrent with the refolding were a number of strike-slip faults striking north-west.

Adopting this, the simplest solution of the network, the phases of movement become as follows. The first phase was folding and faulting equated with the Eugenanan Movement. Fold axes trended 163, axial planes were near vertical, and associated faults dip 45SW179. The second phase was differential folding which formed the Gunns Plains Basin. There was major thrusting at the northern boundary of the basin and minor thrusts elsewhere; fold axes plunge south-west in vertical axial planes; thrusts are oriented 24SW118. This phase is correlated with the Loonganan Movement.

A third phase, possibly contemporaneous with the second, resulted in formation of north-west striking faults with horizontal slip.

Dial Range Trough: At Isandula, near the southern end of the Dial Range Trough, similar-style folds are developed in Cambrian mudstones with an axial-plane slaty cleavage. Data from the Isandula Road yields a beta maximum oriented 18-357 corresponding to a pitch of nineteen degrees north in a modal cleavage plane oriented 80NE354. These folds are correlated with the Eugenanan Movement.

West of Cateena Point the Cambrian mudstones are folded into asymmetrical folds with axes 38-240. Axial surfaces are knick planes which trend to 240 but which dip both south-west and north-east at steep angles. Folds similar to these in profile and orientation have been found at the western side of the Beecraft Megabreccia at Penguin and at Myrtle Creek analogous folds refold "BC" jointing related to north-trending folds. This group of cross-folds with axes trending south-west is identified as Loonganan.

In the Westbank Chaos two periods of folding are inferred. Eugenanan folds have an axial surface transposition foliation oriented 80NE356 with axes pitching twenty-three degrees to the north - a plunge of 22-360. The foliation is superimposed on a megabreccia; across a rock in which each boulder contains a small segment of bedding oriented at random. The deformation resulted in formation of folds with axes at the intersection of foliation with the bedding segments so that the fold axes form a girdle in the foliation. There is a set of "ductile-shear" faults with modal orientation 84L194 probably formed contemporaneously with the Eugenanan folds.

A group of folds with axes modally 10-211 and near-vertical axial surfaces is interpreted as a second phase of folding which is correlated with the Loonganan Movement.

The Westbank Chaos is on the footwall of the Westbank Fault in faulted relationship to the Precambrian of the Goat Island basement wedge. Folds identified as Tabberabberan in this basement wedge are post-metamorphic structures refolding the Precambrian foliation.

Folds of the Eugenanan phase consist generally of minor crenulations of the foliation. Macroscopic folds on the upper plate of the Westbank Fault are upright open folds with axes 16-193 and an axial strain-slip cleavage oriented 78W016. These folds are crossed by superposed Loonganan minor folds with axial planes striking 251 and near vertical, which have axes of variable plunge. The Loonganan minor folds are upright, rounded and symmetrical in areas of flat-lying foliation (the enveloping surfaces are flat-lying) but are steep axial-plunge, asymmetrical folds in steeply-dipping foliation. On the western side of Goat Island, in parts of the Metamorphics and in parts of the Rocky Cape Group, the axial planes are close-spaced penetrative structures.

In the Goat Island Conglomerate the Loonganan folding has the style of knick planes trending (dextral) 297 and (sinistral) 227. A layer of phyllite within the conglomerate has crenulations of this phase plunging 43-230 and 47-301. From these measurements of strikes of knick planes and minor fold axes the orientation of the knick planes is inferred to be 87NE297 and 86NW227. The intersection of the knick planes is within four degrees of vertical. The knick planes are probably superposed on a kinematically passive conglomerate, with principal axes of strain vertical, 0-262, and 0-352. The horizontal plane is the kinematic ac plane and kinematic b is vertical.

Individual knick planes are virtually wrench faults. One, forming the "late cross-fold" on the east side of Goat Island, has very high symmetry. The mean foliation S2 in the conglomerate is intersected and folded about a knick plane nearly normal to S2 and the lineation lying in S2. This results in the lineation being refolded in a girdle normal to the intersection of the knick plane with S2.

Eastern Basement: Minor folds of conjugate profile occur throughout the eastern basement and are similar in style and orientation to Loonganan folds at Goat Island.

The Forth and Ulverstone Metamorphics are regionally refolded on axes trending south-east at Spalford which is probably a Tabberabberan fold.

The Forthside Antiform is a Tabberabberan structure as it also folds overlying Ordovician rocks. There is a discordance in dip of the foliation of the basement, and bedding of Ordovician rocks, at an unconformity, which gives the antiformal axial trace a marked swing in strike at the base of the Ordovician. The antiform is non-cylindrical and in general the Forth Metamorphics show the effect of two phases of post-metamorphic refolding. Schistosity poles tend to form a girdle about the Loonganan axis with Eugenanan axes prominent only in areas near the hinge. The Forthside Antiform is a Eugenanan fold but with the south-west limb refolded in the Loonganan Movement. The deduced axial directions are 12-176 (Eugenanan) and 45-229 (Loonganan) with axial planes near vertical.

<u>Conclusions</u>

The folds formed during the Eugenanan Movement have axial azimuths of 160 to 180 throughout the Dial Range area. The plunges are low and rarely exceed twenty degrees. The large, open upright folds in competent strata are symmetrical. Small folds in steeply dipping foliations in the basement are disharmonic and asymmetrical.

If regional axes <u>A</u>, <u>B</u>, <u>C</u> are erected so that <u>B</u> is near 0-360, and <u>C</u> is vertical, then throughout the region the kinematic <u>ac</u> plane is approximately parallel to <u>AC</u>, and in many areas the kinematic bc plane is parallel to BC, so that after Harland and Bayly (1958) the stress regime is primary thrust. Exceptions are the conjugate-style folds formed during the second generation folding at Mugenana. For these, kinematic a is parallel to C denoting a primary gravity regime. The tear faults on the Gnomon have kinematic b parallel to C implying a primary wrench regime. The primary wrench and primary gravity structures are localised anomalies.

Folds formed during the Loonganan Movement have axial azimuths between 240 to 260. There is usually a single set of axial planes which is vertical and strikes 260 and fold axes lie somewhere in this plane at the intersection of the plane with bedding or foliation. Differences in axial plunge of folds in basement and mantle result from differences in primary orientation of foliation. In some areas there are two sets of axial planes and the folds are conjugate. In these axes of the folds are usually parallel and are parallel to the line of intersection of axial planes but there are areas in which the axes fall into two, non-parallel classes. Folds of this type may be termed "knick-drags" and are due to passive refolding of the foliation about the fault-like knick planes.

If the regional axes A, B, C are used in the same sense as for the Mugenanan Movement, that is, with B 0-350, C vertical, then the broad, open symmetrical folds of low plunge in the mantle have kinematic b parallel to A, that is, they correspond to a secondary thrust regime. However, in steeply dipping areas kinematic b is no longer parallel to A. If the kinematic ac planes for various parts of the terrain are plotted they intersect near 0-350 which is interpreted as the infinity-fold axis of a radial stress field.

Interpretation of the Loonganan stress field as a stress field with radial symmetry and infinity-fold axis 0-350 explains the variation in fold styles. Where bedding or foliation was originally near-horizontal, symmetry planes in common to the stress field and inherited fabric are the horizontal plane (AB in the regional notation), and the planes BC and CA. The symmetrical, upright folds which result reflect the orthorhombic symmetry of this arrangement.

Where the foliation is steeply dipping, the plane of the foliation may either include the infinity-fold axis of the stress system (A) or not. If it does, then the symmetry planes common to the inherited fabric and the stress-field consist of the plane parallel to foliation and the two planes normal to foliation. If the foliation is kinematically active then orthorhombic folds result, which are of conjugate profile with axial planes intersecting in a line parallel to foliation. If the foliation does not include the infinity-fold axis of stress then the only symmetry plane common to the inherited fabric and the stress field is the plane containing the normal to the foliation and the infinity-fold axis of stress. This plane is the single symmetry plane of the monoclinic asymmetrical folds.

In a simple area, such as at Sulphur Creek, the kinematic <u>ac</u> plane for the rocks of the mantle was vertical, whereas in the immediately-underlying basement <u>ac</u> was near horizontal. In terms of bulk deformation there must be additional deformations that were not observed involving distortions in the plane of the foliation in either basement or mantle, such as, for example, an <u>ac</u> jointing in the basement folds. The decollements that occur in part of the Dial Range area may be consequences of accommodation difficulties of this type.

CONCLUSIONS

The major tectonic units in the Dial Range Area include the Lower Division of the Precambrian (Forth and Ulverstone Metamorphics) and the Upper Division of the Precambrian (Rocky Cape Group) which together form the Precambrian basement. The Palaeozoic Dundas Group and Junee Group form the mantle. Rocks younger than Middle Devonian are post-tectonic and include the Eugenanan Beds and the Permian System.

The Lower Division of the Precambrian is characterised lithologically by medium grade metamorphism and structurally by transposition of early S-surfaces into parallelism with the youngest, dominant schistosity S2. There is probably at least one phase of movement with accompanying metamorphism preceding the formation of S2.

Two periods of folding are recognised in the Upper Division of the Precambrian. The first was isoclinal folding with metamorphism of low grade or absent. The second resulted in formation of a schuppen structure in which the beds dip steeply west and are generally overturned. Folds are disharmonic and rest on strike faults which are probably a series of splays from a basal thrust surface. The thrust outcrops at Goat Island and in the country south-west of Ulverstone and is marked in places by a thin layer of chaotic breccia. The thrust is an extremely large structure and probably underlies the Rocky Cape Group throughout Northern Tasmania.

There is no direct correlation that can be made between fold phases in the Metamorphics and phases in the Rocky Cape Group. The second phase of deformation in the Rocky Cape Group has no counterpart of equal intensity in the Metamorphics although a minor crenulation cleavage along a fault zone on Goat Island may belong to this phase. The thrust between the two Precambrian Divisions was a very effective surface of decollement. The youngest phase of deformation in the Metamorphics may correlate with the oldest phase in the Rocky Cape Group in which case there has been "telescoping" of metamorphic facies along the thrust surface.

Precambrian tectonic movements were concluded before the intrusion of the Cooee Dolerites at 700 million years B.P.

The Dundas Group was deposited in a linear trough with long axis directed north from north to south. The base of the Dundas Group rests upon an erosional surface but the trough has probably originated by subsidence of basement blocks. There was considerable erosion within the trough during deposition. In Middle Middle Cambrian time up to 1500 feet of Cateena Subgroup was stripped from certain areas and in Lower Upper Cambrian time at least

500 feet of the Radfords Creek Subgroup together with at least 1000 feet of underlying units was removed at the northern end of the trough. The disturbance in the Middle Cambrian is termed the Hardstaff Movement and the disturbance commencing in the Lower Upper Cambrian is termed the Jukesian Movement, both being "pulses" of the Tyennan Orogeny. The Jukesian Movement has been recognised at many localities in Tasmania, and an unconformity corresponding to the Hardstaff Movement has been deduced on the West Coast by Campana (Banks, 1962, p.130). The Jukesian Movement was accompanied by intrusion of gabbro at the Pieman River on the West Coast of Tasmania, by intrusion of keratophyres in the Dial Range area, and by hydrothermal activity in the Dial Range area and at Zeehan.

The total of the maximum thicknesses of formations in the Dundas Group is close to 10,000 feet but the regions of maximum thickness for the several formations are not coincident and the total thickness of Cambrian sediment in any one place did not exceed 5000 feet. The Dial Range Trough was asymmetrical with a steep western wall against which abutted about 5000 feet of sediment and had a sloping floor on the eastern side. The trough was less than five miles wide. Campana et al (1958) have inferred that there was a rift valley of long duration in the Dial Range area.

Although this "rift valley" was not present in Ordovician time the concept of a graben is applicable to the Cambrian basin.

Campana et al (1958) considered the thick Ordovician conglomerate on the Dial Range to have been deposited in a graben. The conglomerate is not structurally controlled in this fashion.

The Duncan Conglomerate forms a thick, asymmetrical wedge in which bedding has a steeply inclined original dip. The bulk of the rock was derived from Cambrian highlands to the east. The conglomerate has the lithology and form of a terrestrial fanglomerate and forms a talus wedge on the western side of Cambrian mountains. The wedge is up to 1800 feet thick and spreads out on a piedmont to a blanket averaging 650 feet thick. The piedmont cover interfingers down-current with transgressive marine deposits. The Ordovician conglomerates are "post-geosynclinal" and were formed in a subaerial environment. The succeeding marine transgression was widespread and affected the whole of Tasmania.

The Tabberabberan Orogeny occurred in the Middle Devonian. The Precambrian and Palaeozoic rocks were a stratiform pile which deformed heterogoneously. Two principal movement phases are recognised, the Eugenanan and the Loonganan.

The Eugenanan Movement resulted in broad, open, near-cylindrical folds in the competent rocks of the mantle. Interstratified incompetent rocks formed fracture and slaty cleavage and closed, small folds. Deformation of the mantle was thus of the style termed "competent-incompetent". The folds trend north-north-west. In the basement, flat-lying foliations were folded like the beds of the mantle. In steeply-dipping foliations asymmetrical disharmonic folds were formed of small scale - often no larger than crenulations.

In general the Eugenanan stress field was of orthorhombic symmetry and corresponded to the "primary thrust" regime of Harland and Bayly. There are two small areas where exceptions occur but in one case it can be demonstrated that the folds post-date the principal deformation. The exceptions probably result from changes in the relative magnitude of the principal stresses and do not result from changes in the orientation of these stresses.

The Loonganan Movement formed superposed crossfolds in the mantle with sub-horizontal axes which interfere with Eugenanan folds to give large, open, upright, near-cylindrical domes and basins. Folds of analogous style were formed in the basement in areas of flat-lying foliation. In areas of steep dip in the mantle and steep foliation in the basement, asymmetrical minor folds were formed at the intersection of their constantly-oriented axial planes and foliation. For the region as a whole it is found that kinematic <u>ac</u> planes intersect in a direction ten degrees west of north which is interpreted as the infinity-fold axis of a radial stress system. Minor folds of conjugate profile occur where the inherited foliation plane included this infinity-fold axis.

The Tabberabberan Orogeny resulted in an orthorhombic Eugenanan stress field succeeded by an axial Loonganan stress field. In terms of stress regimes, a primary thrust regime was followed by a secondary axial regime, both of long duration. There is evidence of short-lived primary gravity and primary wrench regimes between the two long-lived phases and of a succeeding secondary wrench regime. The variations between these stress fields are variations in the relative magnitude of the principal stresses and not variations in orientation. This supports stratigraphic evidence which shows that post-Ordivician deformation occurred in a single orogeny during the Middle Devonian.

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Appendix 1

The Tertiary Stress Field

From the data at the Illamatha Colliery, the stress field at the time of the normal, or graben-forming, faulting, may be determined after the methods of Anderson (1951, pp.11, 155).

Using Anderson's terminology, the measurements of the fault surfaces yield:

θ is near 20 degrees
μ is 1.191
$\underline{n}$ is 7.544.

The mean density of overburden is assumed to be 165 lbs wt per cubic foot, whence $\underline{P}$ is 1.1$\underline{Z}$ lbs wt per square inch ($\underline{Z}$ in feet).

$\underline{P}_o$ is assumed to be 740 kilograms per square centimetre, or 10,520 lbs per sq. inch.

After Anderson, the condition for normal faulting is

$$\underline{P}_n = \underline{P} - \underline{P}_o$$

whence $\underline{R} = 0.1458\,\underline{Z} - 1395$

This yields a depth of zero tension of 9565 feet. It has been shown that the maximum cover at the Illamatha was 2000 feet at the time of faulting, which implies the region was in tension at this time. This is expected, from the occurrence of the ductile shear folds.

More than this, however, the existence of the folds is due to separation of the walls of the faults - i.e. there was a component of tension normal to the fault planes. The conditions on the fault plane may therefore be calculated using the relation established above.

If $\underline{N}$ is the pressure normal to the fault plane, then for a fault hading 70 degrees,

$$\underline{N} = \underline{P} \cos 70 + \underline{R} \cos 20$$

$$\text{whence} \quad \underline{N} = 0.5133\,\underline{Z} - 1311$$

This relation yields $\underline{N}$ zero at a depth of 2,554 feet. Ductile shear folds would not be expected to form at a greater depth than this, as at greater depths, there is no stress component tending to open the faults.

The depth of 2,554 feet agrees well with the geology of the region, which indicates that at the time of faulting the depth of burial was less than 2,000 feet.

<u>Reference</u>

Anderson, E.M. (1951) "The Dynamics of Faulting" 2nd ed., Oliver and Boyd, London, 206pp.

Appendix 2

Convergence of Flow Lines

Convergence of flow lines, or 'pq' surfaces, may be due to thermal changes in the rock (Carey, 1954) or to inhomogeneity of the flowing body. The second case is considered here, in its two-dimensional aspects.

Flow lines may be defined as lines which are everywhere tangential to the displacement of particles. Hence there is no component of displacement transverse to flow lines.

Consider a pair of flow lines crossing an interface between regions of differing Newtonian viscosity. The direction of flow is up the page in the figure.

If **w** is the width of the flow layer in the lower medium, and **w'** the width in the higher; and if **s** and **s'** are the displacements along the flow lines in each medium, then if α is the angle of shear,

$$s' = w' \tan\alpha'$$
$$s = w \tan\alpha$$

In the horizontal direction, the rate of change of displacement is $\frac{\partial s}{\partial x}$ and $\frac{\partial s'}{\partial x'}$,

where $$\frac{\partial s'}{\partial x'} \Big/ \frac{\partial s}{\partial x} = \frac{w'\tan\alpha'}{w'} \Big/ \frac{w\tan\alpha}{w} = \frac{\tan\alpha'}{\tan\alpha} \quad \ldots\ldots (1)$$

If the displacement occurred in the same stress field, with shear stress τ, and a velocity of motion $U = \frac{\partial s}{\partial t}$, then $$\eta' \frac{\partial}{\partial x}\left(\frac{\partial s'}{\partial t}\right) = \eta \frac{\partial}{\partial x}\left(\frac{\partial s}{\partial t}\right)$$

and provided that $$\frac{\partial}{\partial x}\left(\frac{\partial s}{\partial t}\right) = \frac{\partial}{\partial t}\left(\frac{\partial s}{\partial x}\right)$$

then $$\eta' \frac{\partial}{\partial t}\left(\frac{\partial s'}{\partial x}\right) = \eta \frac{\partial}{\partial t}\left(\frac{\partial s}{\partial x}\right)$$

Since the deformation of each region occurred in the same time, integrating with respect to this time,

$$\eta' \frac{\partial s'}{\partial x} = \eta \frac{\partial s}{\partial x}$$

i.e. $$\frac{\partial s'}{\partial x} \Big/ \frac{\partial s}{\partial x} = \eta / \eta' \quad \text{. . . . . . (2)}$$

Comparing (1) and (2),

$$\eta / \eta' = \tan\alpha' / \tan\alpha \quad \text{. . . . . (3)}$$

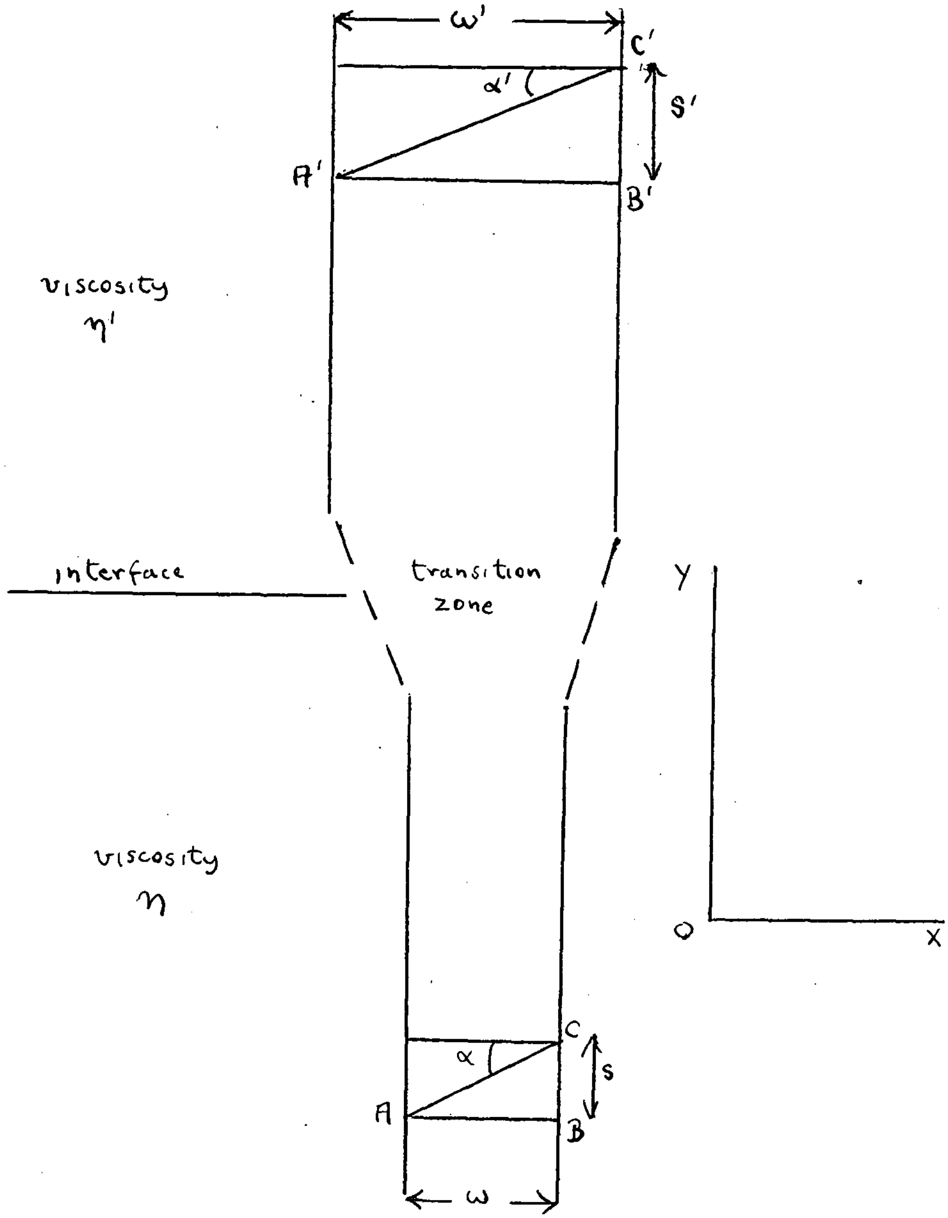
That is, the tan of the angle of shear is inversely proportional to the viscosity, η.

Since volume is conserved (there being no transport across flow lines), the area ABB'A' is equal to the area of ACC'A'. That is, the material emerging at the top (area A'B'C') is equal to the material entering at the bottom (area ABC).

Hence $$\tfrac{1}{2} w's' = \tfrac{1}{2} w s$$

$$\tfrac{1}{2} w'(w' \tan\alpha') = \tfrac{1}{2} w (w \tan\alpha)$$

$$\frac{\tan\alpha'}{\tan\alpha} = \left(w/w'\right)^2 \quad \text{. . . . . (4)}$$



ω'
C'
α'
S'
A'
B'
viscosity
η'
interface
transition
zone
Y
viscosity
η
O
X
C
α
s
A
B
ω

It may be noted that this conservation principle implies that the flow lines can be lines of equal displacement only if there is no convergence.

From (3) and (4),

$$(\omega/\omega')^2 = \eta/\eta' \quad \cdots\cdots (5)$$

that is, the width of the flow lines is proportional to the square root of the viscosity.

In the example quoted in Chapter 6 for chert/limestone,

$$\omega'/\omega = 12/10$$
$$(\omega'/\omega)^2 = 144/100$$

i.e. $\eta/\eta' = 144/100$, that is, the chert is about half as viscous again as the limestone.

This treatment is a static one, in the sense that the width of the flow lines remains constant. However, the width should change extremely slowly in comparison with the other quantities (mainly the vertical extension) so this is not an important source of error.

According to Jaeger (1962, p.32), the effective shear strain, $\tan \alpha$, is, in pure shear, given by

$$\tan \alpha = (k^2 - 1)/k.$$

In the example, the elongation of the chert was estimated, from the curvature of the generating surface, to be 110 percent, and for the limestone, from the deformed fossils, to be 180 percent. Using the formulae $y' = ky$; $x' = x/k$ (transformation equations for pure shear), and the relation $k = (100 + \gamma)/100$, where γ is the percentage elongation, we obtain

$$\text{for the chert, } k = 2.1$$
$$\text{for limestone, } k = 2.8$$

whence for the chert, $\tan \alpha' = 1.62$

and for limestone, $\tan \alpha' = 2.44$

from which, for chert/limestone,

$$\eta / \eta' = \tan \alpha' / \tan \alpha = 2.44/1.62 = 1.51.$$

In summary, it has been shown that a comparison of the deformation of chert and limestone, by means of a flow net, yields a ratio of viscosities for the chert/limestone of 144/100. By consideration of bulk strains from two entirely different structures, namely deformed fossils, and curvature of the generating surface of a group of folds, the ratio of viscosities has been again calculated, yielding 151/100.

The agreement between the two sets of figures is remarkable, considering the fragmentary data on which the second calculation is based. Very few highly deformed fossils were observed, and the generating surface was not long enough to adequately define inflection points. An agreement within thirty percent would have been considered significant. However, as Cloos has shown in the South

Mountain fold of Maryland, deformation of this kind is very uniform over quite large areas, and this is presumably the case at Eugenana, where all the observations were made in a single quarry.

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Appendix 3

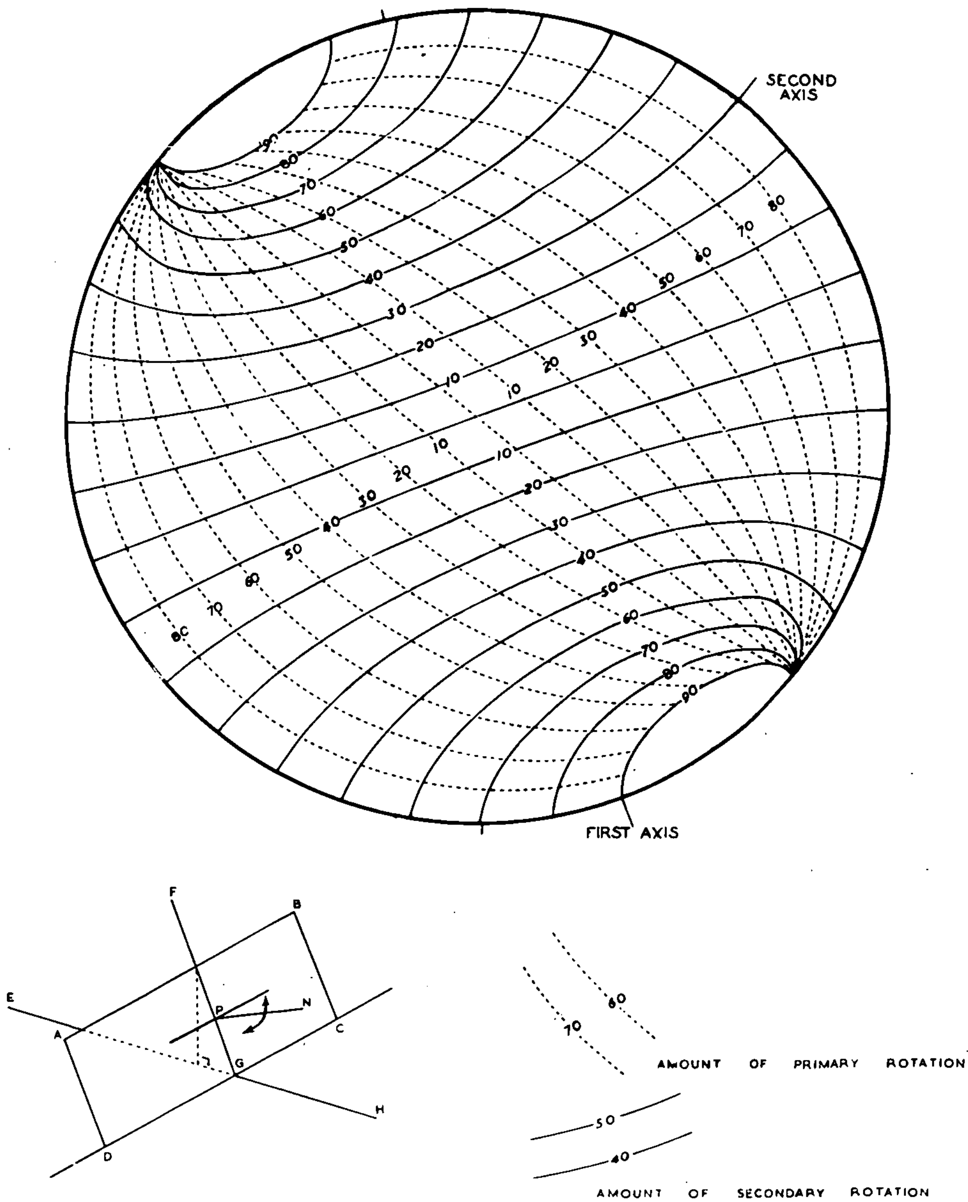
Beta diagrams in non-cylindrical folding

The geometry of superposed folding has been described by Weiss (1959), and the resulting beta-diagrams by Lindstrom (1961).

Referring now to the diagram of figure 1, in flexural folding bed ABCD is refolded about the line FG. FG is the trace of the axial plane EFH of the second generation of folding, on ABCD. The normal to ABCD, or pole in projective geometry, represented by PN, is rotated in a plane normal to FG. The first beta is BC, the second is FG. The line EH is the second trend.

The nomogram of figure 1 was constructed on the basis of this mechanism. An originally horizontal bed is doubly folded. If the pole is plotted on the net, the amounts of primary and secondary rotation can be read directly. This enables the successive rotations of any element of the doubly folded terrain to be determined. Alternatively, assuming two arbitrary profiles, it enables a map of the crossfolded terrain to be constructed (figure 2).

In figure 2, the map of the flexurally crossfolded



NOMOGRAM

UNWINDING FLEXURAL CROSSFOLDING

Figure 1

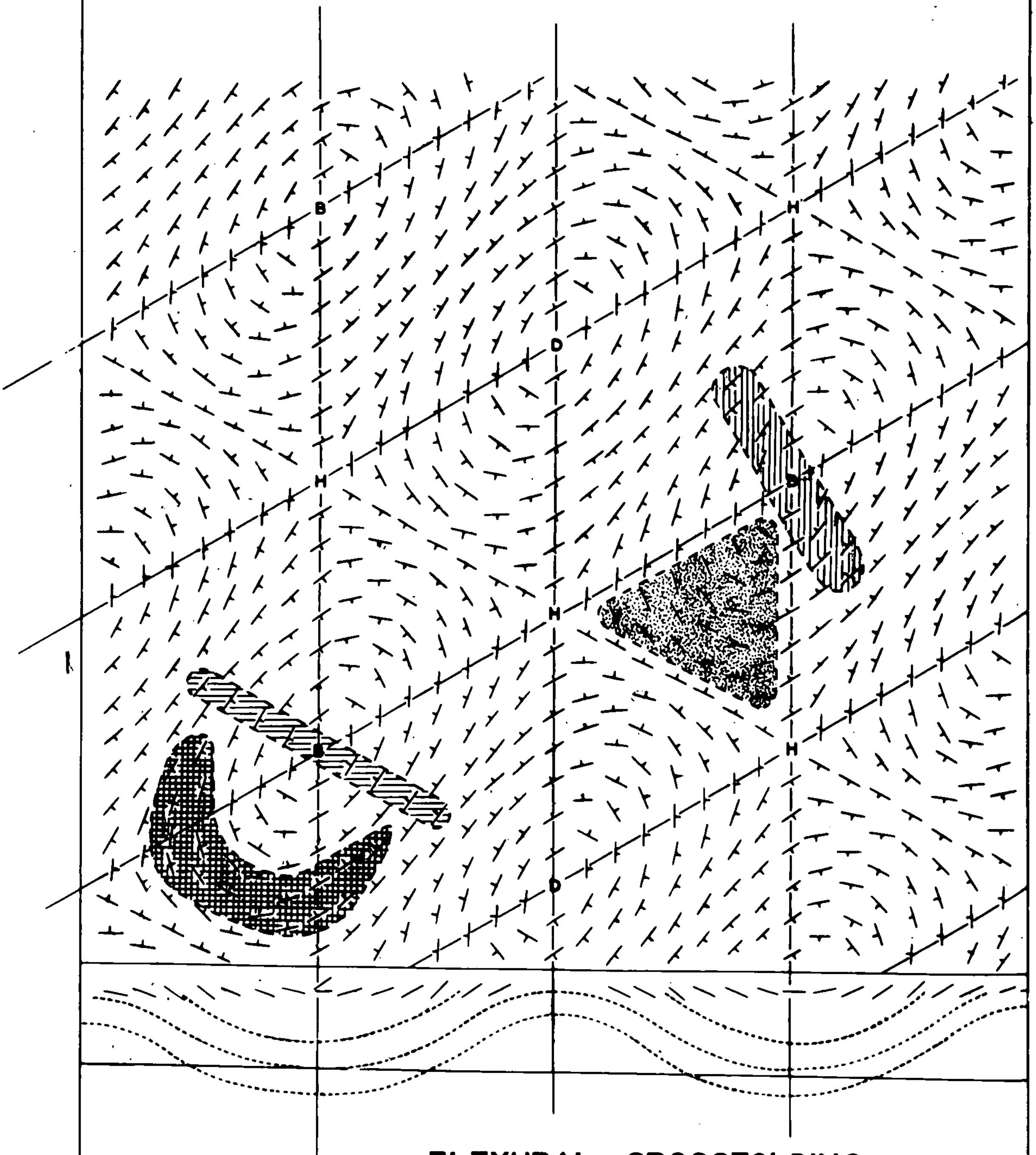
terrain, arbitrary subareas W, X, Y, and Z are indicated. Beta diagrams for these subareas are shown in figure 3. Subarea W yields two significant, and one spurious, maximum. In subarea X, corresponding to a traverse around the rim of the basin, only a spurious maximum is obtained. The spurious maxima can be very high, as shown by subareas Y and Z.

The orientation of the spurious maxima is governed by the basin shape. The seventy-three percent maximum of subarea Y, for instance, defines the direction of the longer axis of symmetry of the basin. The symmetry axes bisect the fold trends.

The map of figure 2 is constructed with a limited number of dips. If a complete map were available, a traverse through the centre of the basin, along one of the axes of symmetry, should yield a 100 percent beta-maxima oriented parallel to the other axis of symmetry. At traverse through the centre of the basin, along the lines H-B-H or H-D-H, should yield a 100 percent maximum oriented parallel to the fold trends.

In folding in which the axes of basin and dome symmetry are not parallel to the constituent trends, beta maxima will be obtained which reflect not only the fold trends, but fold symmetry, as well.

This problem arises in superposed shear folding.



SUBAREA Z

SUBAREA Y

SUBAREA X

SUBAREA W

FLEXURAL CROSSFOLDING

COMPUTED PATTERN

D=DOME POINT

B=BASIN POINT

H=HYPERBOLIC POINT

Figure 2

O'Driscoll (1962, figure 2) and Ramsay (1962, figure 3) show that superposed similar folds have axes of symmetry oblique to the constituent trends. In this case, the folds will be elongated in a direction nearest to the trend with greatest vertical movement.

The size of beta maxima in non-cylindrical folds indicates, then, the symmetry of the fold as well as the position of the constituent fold trends. A sufficient number of random traverses of a flexurally formed, non-cylindrical fold, should yield four directions with high maxima. With a certain amount of random scatter, beta diagrams could soon be useless, requiring the application of other methods of analysis.

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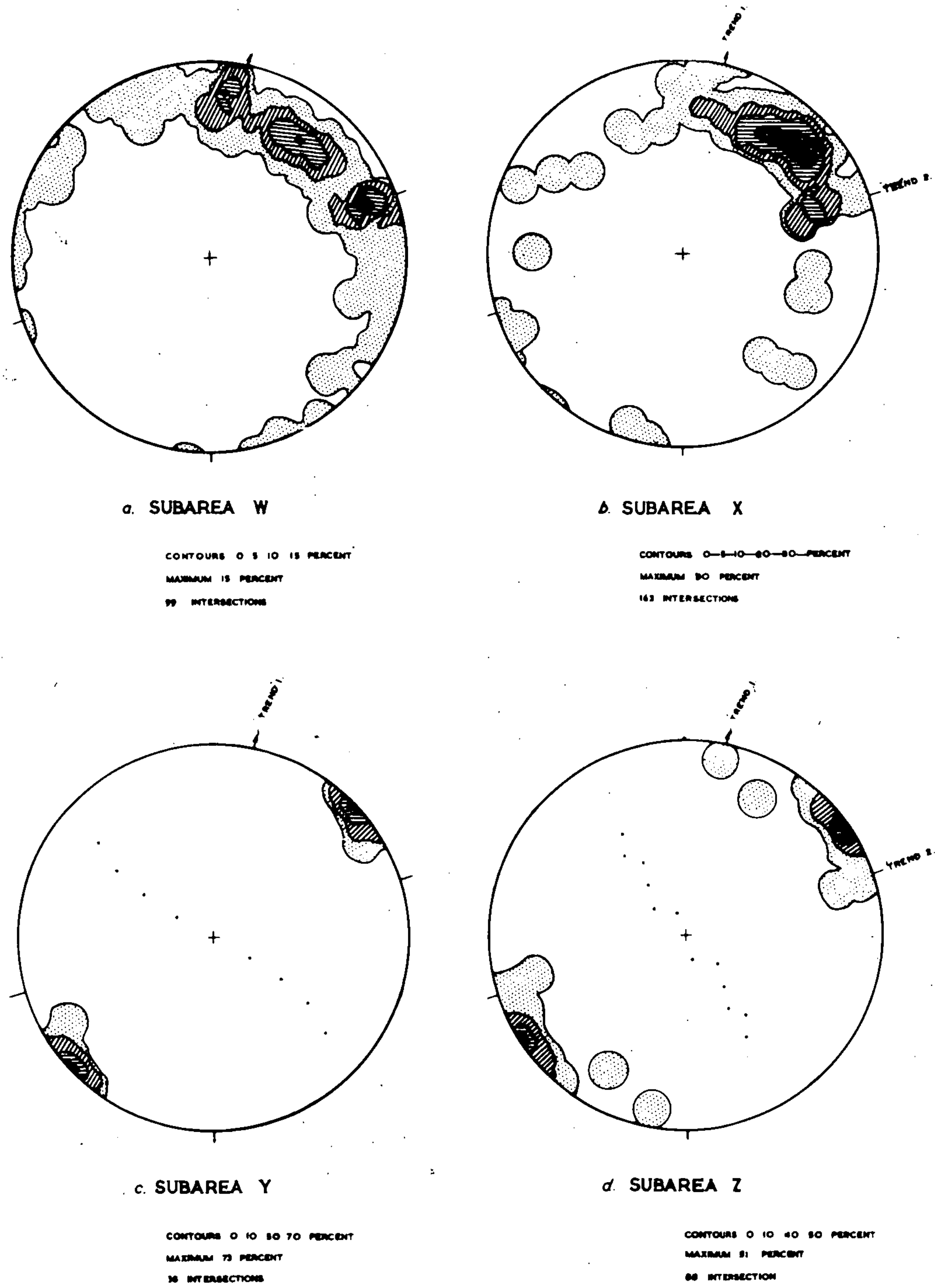

β - DIAGRAMS OF HYPOTHETICAL CROSSFOLDING

Figure 3

Lower Palaeozoic Rocks of the Dial Range:
Stratigraphic Terminology.

K. L. Burns.

1. INTRODUCTION

The stratigraphic terminologies of Burns (1963a, 1963b) do not comply with all the conditions laid down by the Australian Code of Stratigraphic Nomenclature. However, it was considered that his work was not proceeding *in vacuo* but against a background of nomenclature in widespread and general use. The failure to comply with the Code was not a consequence of failure to understand the Code, but was a decision made after careful deliberation and in what was believed at the time to be in the best interests of geology and of fellow-workers, and was made in view of the statement of the Australian Committee on Stratigraphic Nomenclature (1953, p.125):

> "The Committee ..... does not wish to be considered as a body charged with the responsibility of drafting and enforcing a rigid set of rules."

However, objection has been taken to the procedures that were followed, and upon re-consideration of the matter it is conceded that, in the present instance, there are advantages to be gained from adherence to the Code. Accordingly, a revised terminology is presented which conforms to the letter of the Australian Code.

A formal terminology and definitions for the stratigraphic succession in the Dial Range has not yet been published, Banks (1962) being a provisional column, and Burns (1963a) being a diagrammatic presentation only. However, in the enclosed Stratigraphic columns, these are treated as formal lists and in the discussion that follows, are compared with each other and with the revised terminology of columns 4 and 6. The greatest variations in terminology occur in the Cambrian System and these are discussed first. The variations in terminology applied to the Ordovician System are not essentially different in character.

Consideration has been given to the manner of erection of Sub-Groups and Super-Groups, and to the application of the term Group. As these considerations do not fit directly into the principal discussion, the results are stated in separate concluding sections.

2. CAMBRIAN SYSTEM

Introduction: Four stratigraphic columns are shown (columns 1 to 4) which show the nomenclature of Banks (quoting Burns, 1962), Burns (1963a), Burns (1963b), and the revised terminology of Burns (1964).

Differences between these columns may be classified as differences in nomenclature, differences in interpretation, and differences in terminology.

Differences in Nomenclature: The name "Kateena" was submitted to the Tasmanian Nomenclature Committee, a statutory body with powers of regulation under Act of the Tasmanian Parliament, as a new name for a point of land in the Leven River estuary. This name, along with other names submitted but not then ratified, was utilised for the version shown in column 1. However, after a delay of nearly two years, the Nomenclature Committee adopted the name "Cateena" in place of "Kateena".

The name "Kateena" in column 1 is therefore invalid as it applies to no topographic feature and it was replaced by the name "Cateena" in subsequent stratigraphic columns.

Differences in Interpretation: The Westbank Beds in column 1 are indicated as younger than the Tea Tree Point Megabreccia. This is probably true, but cannot be proven at this stage, so in subsequent versions it was felt better to list only the Beecraft Megabreccia (which is the best development of this lithology) and to indicate the Westbank Beds and the Tea Tree Point Megabreccia as correlatives.

Banks (1962, figure 11, p.139) considered that the Beecraft Megabreccia and its correlatives unconformably overlies the Radfords Creek unit. Burns, in columns 1, 2, and 3, considered the Beecraft Megabreccia to be a facies variant within the Radfords Creek unit. The question of an unconformity cannot be decided without additional information, but consideration of the matter during compilation of column 4 led to the conclusion that the weight of evidence is in favour of Banks' interpretation. Consequent upon this change of opinion, the terminology was adopted as in column 4. This alteration is felt to represent a considerable improvement in objectivity and clarity.

Differences in Terminology: Terminological differences between the stratigraphic columns numbered 1 to 4 are of four kinds. First, some Formations of column 1 are upgraded to units of higher rank in subsequent columns. Second, the Sub-Groups of column 2 were given lithological characterization which was abandoned in later columns. Third, the term Sub-Group was used in column 3 and was replaced by Group in later columns. Fourth, the term Dundas Group was used in column 2 but was replaced by the term Cambrian System in later columns.

(1) In column 1 the Radfords Creek and Cateena units are designated as Formations. This was, however, only a provisional column and in subsequent columns these Formations were upgraded to units of higher rank (Groups in column 4). This upgrading was a result of the discovery that the units are substantial units which can be traced for many miles - more than twenty miles for the Cateena unit - and by the realisation that the units were being identified as combinations of units of lower rank so that the term Group is more appropriate than Formation, as is discussed in section 4.

This change in designation of the units was made in accordance with the second edition of the Australian Code of Stratigraphic Nomenclature (1956a, article 25, p.120).

(2) The Radfords Creek and Cateena Sub-Groups of column 2 were given lithological characterization in accordance with the International Code of Stratigraphic Terminology which states (Hedberg, 1961, article B6, p.22):

> "Generally it is not possible to characterize the lithology of a group in its name although, where readily feasible, it is desirable to do so."

However, the International Code (1961, p.11) and the Australian Code (1956a, article 20, p.119) require that, in addition to the lithological term, the rank of the term should be designated in the case of units other than a Formation. Thus column 2 should have read "Radfords Creek Mudstone Sub-Group" and "Cateena Mudstone Sub-Group" in order to convey the sense intended. This source of confusion was eliminated in columns 3 and 4.

(3) The term Sub-Group was used in column 3 in places where the term Group was used in column 4. Column 3 was in error, and this was corrected in column 4. There is

a different procedure required for the establishment of a Group as against a Sub-Group, as is discussed in section 4. However, the error in terminology of column 3 was not a direct result of faulty procedure of this type, but a consequence of the correct procedure being applied to a faulty premise. Given that the succession is correctly entitled "Dundas Group", then the units in question are correctly entitled "Sub-Group" in accordance with the Australian Code (1963, p.123; 1956a, article 15; 1959, article 15). However, as is discussed below, the succession is not correctly entitled Dundas Group.

(4) The term Dundas Group was applied to the succession in columns 2 and 3, whereas the term Cambrian System is applied in column 4. These different terms represent different answers to the question: "If there is an established Group, how far from the type area is the Group name applicable?"

This question is discussed at length in section 5, where it is concluded that a Group extends no further than its constituent Formations. As soon as these Formations are no longer recognisable, or their mutual relationships have significantly changed, the Group is no longer identifiable and the Group name is no longer validly applied. The name Dundas Group was therefore incorrectly applied to columns 2 and 3, an error which was corrected in column 4.

3. ORDOVICIAN SYSTEM

Columns 5 and 6 show the various terminologies applied to the Ordovician System. Column 6 is the corrected version, and results from the recognition that the term Junee Group is not applicable to the Dial Range succession, for reasons which are the same as for the comparable term, Dundas Group. The name Junee Group being no longer applicable, the term Sub-Group was inappropriate, and the appropriate term Group was substituted.

4. PROCEDURES FOR ERECTION OF SUB-GROUPS

The terms Group and Sub-Group are ranking terms in the formal hierarchy of the Australian Code of Stratigraphic Nomenclature (Raggatt, 1950, article 16; 1956a, articles 14, 15; 1959, articles 14, 15). The term supergroup (sic) is permitted in the International Terminology (Hedberg, 1961, article B6, p.22).

Article 15 of the third edition of the Australian Code (Raggatt, 1959) states... "The term 'Sub-Group' may be used in the same sense as 'Group'." This does not mean that the term Sub-Group is to be established by the same procedures as in the establishment of the term Group. An example of the appropriate procedure is given in the commentary of 1953 (p.123) where, in the interests of nomenclatural stability (in accordance with article 14b of the first edition of the Australian Code (1950)), the introduction of Sub-Groups permits the early name Narrabeen (Group) to be retained. This procedure is affirmed in articles 15 of the second and third editions of the Australian Code (1956a, 1959).

If the term "analytical" is used with the meaning "formed by sub-division of" and the term "synthetic" with the meaning "formed by grouping together" as in Raggatt (1956a, article 14), then Formation is an analytical term, Group is a synthetic term, and Sub-Group is a an analytical term.

In particular, Group is a synthetic term, and a Group is constructed by the grouping together of Formations. In this context it is considered that the commentary to article 16 of the first edition of the Australian Code (1950, p.173) is in error where it permits Groups to be erected in expectation of subsequent sub-division.

A Sub-Group is an analytical term, and a Sub-Group is established by sub-dividing a previously-established Group. A Sub-Group is not established by the grouping together of Formations even though a Sub-Group will consist of a number of Formations.

A Super-Group is a synthetic term, not recognized in the Australian Code, formed by the assembling together of previously-established Groups.

5. APPLICATION OF THE TERM GROUP

The International Code of Stratigraphic Terminology (1961, p.11) and the third edition of the Australian Code of Stratigraphic Nomenclature (1959, p.65) define a Group as an assembly of Formations. This is, of course, not an indiscriminate assembly, but the Formations so assembled must be juxtaposed and have some lithogenetic features in common. The Dundas Group is, therefore, the collection of Formations which includes the Judith Slate and Tuff below and the Misery Conglomerate above, with the mutual relationships and lithogenetic characters such as are found in the Dundas area. Applying a rigid interpretation of the Codes, the Dundas Group may only be recognized in areas in which these delimiting Formations are recognized.

This interpretation is in agreemeht with the International Code of Stratigraphic Terminology, which states (1961, p.11):

> "The extent of a lithostratigraphic unit should be controlled by the extent of the distinctive lithologic features on which the unit was based in its standard reference sections...."

A Formation may be distinguished by a number of characters, such as a preponderance of certain petrological types, but such characters are inadequate to distinguish Groups as Groups are defined in a different manner to Formations. The distinctive features that characterise a Group are the occurrence of designated Formations in specific mutual relationship. As soon as these Formations are no longer recognizable, or their mutual relationships have significantly changed, the Group is no longer identifiable and the Group name is no longer validly applied.

This strict interpretation of the Code has not been generally applied in Tasmania. For example, although Blissett and Gulline (1962) show "Unassigned Dundas Group" north of the Pieman River, the Dundas Group does not extend any further north than its northernmost Formation (the Razorback Conglomerate, at latitude 41°49'S). From a strict viewpoint, the term "Unassigned Dundas Group" is, in fact, nonsense. However, the term has always been well-understood in practice. Another example is contained in the "Geology of Tasmania", J. geol. Soc. Aust. Vol.9 Pt.2 (1962) p.194. In one place the term Quamby Group is applied to a single Formation, the Quamby Mudstone. In another place the term Quamby Group is applied to a collection of Formations with names Woody Island, Sunset Bay, Satellite, D'Entrecasteaux, Lewis Point, Alonnah, and Dreamy Bay. This usage does not conform strictly with the Codes, but has been accepted practice and is widely used and is well understood.

The possibility of walking the outcrop between different areas is of no direct significance in the extension of the term Group from one area to another. It is possible, for example, excepting minor interruptions of Cainozoic rocks, to walk on Cambrian rocks from Dundas to the Dial Range, as is shown by mapping of McKenna, Dickinson, and others. However, the term Dundas Group is not validly extended to the Dial Range unless the Formations that characterize the Group can be shown to extend that far. Walking the outcrop is a method of identifying Formations, but has no direct meaning in connection with Groups.

In the context of a Geological Survey, even though there may be continuity of Formations from one area to another, it may require the publication of Formation standard maps of the intervening areas to provide valid documentation of continuity.

6. STRATIGRAPHIC COLUMNS

Column 1

Published in Banks (1962, p.134).

Westbank Beds
Tea Tree Point Megabreccia
Radfords Creek Formation
Motton Spilite
Barrington Chert
Hardstaff Unconformity
Kateena Formation
Lobster Creek Volcanics.

Column 2

Published in diagrammatic form in Burne (1963a).

DUNDAS GROUP
RADFORDS CREEK MUDSTONE
Beecraft Megabreccia
Mudstone (mainly)
Applebee Volcanics
Mudstone (mainly)
Motton Spilite
Barrington Chert
Unconformity
CATEENA MUDSTONE
Mudstone (mainly)
Wilsonia Volcanics
Mudstone (mainly)
Kerrison Volcanics
Mudstone (mainly)
Isandula Road Conglomerate
Lobster Creek Volcanics.

Column 3

Unpublished column in Burns (1963b, p.78).

DUNDAS GROUP
RADFORDS CREEK SUBGROUP
Beecraft Megabreccia and correlatives
Mudstone, sandstone and conglomerate
Applebee Creek Volcanics
Mudstone, sandstone and conglomerate
Disconformity
Motton Spilite
Barrington Chert
Hardstaff Unconformity
CATEENA POINT SUBGROUP
Mudstone, sandstone and conglomerate
Wilsonia Creek Volcanics
Mudstone and sandstone
Kerrison Creek Volcanics
Mudstone, sandstone, claystone and conglomerate
Isandula Conglomerate
Disconformity
Lobster Creek Volcanics.

Column 4

(Revised column published in Burns (1964, in press)

CAMBRIAN SYSTEM
Beecraft Megabreccia (and correlatives: Tea Tree Point Megabreccia Westbank Beds) equivalent to, or unconformably overlying the Radfords Creek Group.
RADFORDS CREEK GROUP
Mudstone, sandstone and conglomerate
Applebee Volcanics
Mudstone, sandstone and conglomerate
Disconformity?
Motton Spilite
Barrington Chert
Hardstaff Unconformity
CATEENA GROUP
Mudstone, sandstone and conglomerate
Wilsonia Volcanics
Mudstone and sandstone
Kerrison Volcanics
Mudstone, sandstone, claystone and conglomerate
Isandula Road Conglomerate
Disconformity?
Lobster Creek Volcanics.

Column 5
Unpublished column in Burns (1963b, p.

JUKES GROUP
Gordon Limestone
DIAL SUBGROUP
Moina Sandstone
Duncan Conglomerate
Gnomon Mudstone.

Column 6
Burns (1964, in press).

ORDOVICIAN SYSTEM
Gordon Limestone
DIAL GROUP
Moina Sandstone
Duncan Conglomerate
Gnomon Mudstone.

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